

# NAVAL POSTGRADUATE SCHOOL

## Monterey, California



## DISSERTATION

### ELECTROMAGNETIC SCATTERING OF AN ANISOTROPICALLY COATED TUBULAR CYLINDER

by

Chen-Kuo Yu

March, 1997

Dissertation Supervisor:

Hung-Mou Lee

Approved for public release; distribution is unlimited.

19971125 021

THIS QUALITY INSPECTED 4

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE March 1997.		3. REPORT TYPE AND DATES COVERED Ph.D. Dissertation
4. TITLE AND SUBTITLE ELECTROMAGNETIC SCATTERING OF AN ANISOTROPICALLY COATED TUBULAR CYLINDER			5. FUNDING NUMBERS	
6. AUTHOR(S) Chen-Kuo Yu				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey CA 93943-5000			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.			12b. DISTRIBUTION CODE	
13. ABSTRACT (maximum 200 words) The sum-difference surface current formulation is introduced to treat electromagnetic boundary value problems when anisotropic impedances are specified on both sides of a surface. It can also be applied to impedance coated bodies. This formulation preserves the duality nature of Maxwell equations and carries it over into the algebraic form of the integrodifferential operators in the equations for surface currents. Since a 90° rotation is equivalent to undergoing a duality transform for an incident plane wave, this particular symmetry in the algebraic form of the operators leads to sufficient conditions under which the on-axis backscattering of an anisotropic impedance coated scatterer having a 90° rotational symmetry is eliminated. The sum-difference formulation is utilized for solving the problem of electromagnetic scattering from an anisotropically impedance coated tubular cylinder of finite length. The solution has been coded in FORTRAN and tested. Some interesting results are presented and discussed.				
14. SUBJECT TERMS zero backscattering cross section, impedance boundary condition, anisotropic surface impedance			15. NUMBER OF PAGES 127	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)  
Prescribed by ANSI Std. Z39-18 298-102



**ELECTROMAGNETIC SCATTERING  
OF AN ANISOTROPICALLY COATED TUBULAR CYLINDER**

Chen-Kuo Yu  
Captain, Republic of China Navy  
B.S., Chinese Naval Academy, 1976  
M.S.S.E., Naval Postgraduate School, 1990

Submitted in partial fulfillment of the requirements for the degree of

**DOCTOR OF PHILOSOPHY IN (Electrical Engineering)**

from the

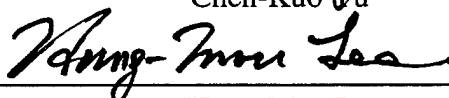
**NAVAL POSTGRADUATE SCHOOL  
March 1997**

Author:



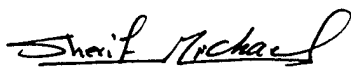
Chen-Kuo Yu

Approved by:

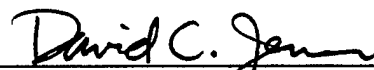


Hung-Mou Lee

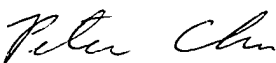
Associate Professor of Electrical and Computer Engineering,  
Dissertation Supervisor



Sherif Michael  
Associate Professor of  
Electrical and Computer Engineering



David C. Jean  
Associate Professor of  
Electrical and Computer Engineering

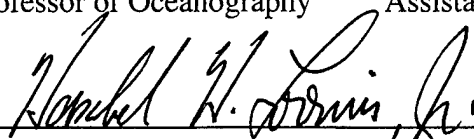


Peter C. Chu  
Associate Professor of Oceanography



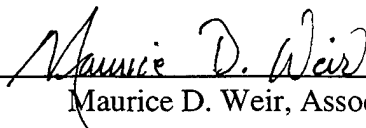
Fariba Fahroo  
Assistant Professor of Mathematics

Approved by:



Herschel H. Loomis, Jr., Chair, Department of  
Electrical and Computer Engineering

Approved by:



Maurice D. Weir, Assoc. Provost for Instruction



### **Abstract**

The sum-difference surface current formulation is introduced to treat electromagnetic boundary value problems when anisotropic impedances are specified on both sides of a surface. It can also be applied to impedance coated bodies. This formulation preserves the duality nature of Maxwell equations and carries it over into the algebraic form of the integrodifferential operators in the equations for surface currents. Since a  $90^\circ$  rotation is equivalent to undergoing a duality transform for an incident plane wave, this particular symmetry in the algebraic form of the operators leads to sufficient conditions under which the on-axis backscattering of an anisotropic impedance coated scatterer having a  $90^\circ$  rotational symmetry is eliminated. The sum-difference formulation is utilized for solving the problem of electromagnetic scattering from an anisotropically impedance coated tubular cylinder of finite length. The solution has been coded in FORTRAN and tested. Some interesting results are presented and discussed.



## TABLE OF CONTENTS

I. INTRODUCTION .....	1
II. THE SUM-DIFFERENCE SURFACE CURRENT FORMULATION OF ELECTROMAGNETIC BOUNDARY-VALUE PROBLEMS .....	5
A. STRATTON-CHU FIELD FORMULATION AND RADIATION .....	5
B. CONDITION ON THE CURRENTS IMPOSED BY MAXWELL EQUATIONS .....	7
C. IMPEDANCE BOUNDARY CONDITION .....	9
D. ALGEBRA OF THE SUM-DIFFERENCE CURRENT EQUATIONS .....	11
E. CONSIDERATIONS FOR A CLOSED SURFACE .....	14
III. A THEOREM OF ANISOTROPIC ABSORBERS .....	15
A. AXIAL RADIATION FROM A SURFACE OF $90^\circ$ ROTATIONAL SYMMETRY .....	15
B. CONDITION FOR VANISHING ON-AXIS BACKSCATTERING ...	17
C. IMPEDANCE MATRICES FOR ZERO ON-AXIS BACKSCATTERING .....	21
IV. SCATTERING OF AN ANISOTROPICALLY COATED CYLINDER .....	25



A.	GEOMETRY AND COORDINATE SYSTEM .....	25
B.	SCATTERED FIELDS .....	27
C.	TRANSFORM TO SYSTEM OF LINEAR EQUATIONS .....	34
1.	Incident Fields .....	35
2.	The $R$ - Matrix Term .....	37
3.	The Operators .....	38
D.	RADIATION IN THE FAR FIELD .....	43
E.	INSIDE AND OUTSIDE SURFACE CURRENTS .....	45
V.	COMPUTATION AND RESULTS .....	47
A.	COMPARISON WITH EXPERIMENTAL DATA .....	47
B.	NULL ON-AXIS BACKSCATTERING .....	48
C.	FREQUENCY DEPENDENCE .....	49
D.	COMPUTATION ACCURACY .....	50
VI.	CONCLUSIONS .....	67
APPENDIX	PROGRAM LISTING .....	69
A.	INCLUDE FILES .....	69
B.	INPUT DATA FILES .....	69
C.	SETUP PROGRAM AND CREATED FILES .....	70
D.	PROGRAM MAIN .....	71

E.	SUBROUTINE CHKINPUT .....	72
F.	SUBROUTINE MAXODM .....	74
G.	SUBROUTINE RAPQMT .....	75
H.	SUBROUTINE GNPQFN .....	81
I.	SUBROUTINE BCKSCFL .....	92
J.	SUBROUTINE RCSPAREA .....	111
LIST OF REFERENCES .....		113
INITIAL DISTRIBUTION LIST .....		115

## I. INTRODUCTION

Sometime ago the question was raised: "For electromagnetic boundary value problems with specified surface impedances, how can one go from a non-perfectly conducting surface on which both the electric and the magnetic equivalent surface currents are to be found, to a perfectly conducting surface on which the number of unknowns is halved [1]?" The answer to this question turns out to be one of algebra. It is well known that the impedance specified on the surface of a body separates its interior completely from its exterior. Therefore an impedance coated body can always be considered as a hollow volume enclosed by an infinitesimally thin shell with surface impedances specified both on the inside and the outside of the shell. The inside and the outside of the body can be considered as constituted of the same medium and the impressed electromagnetic excitation can be treated as continuous across the shell. On the outside surface, there are the equivalent total electric current  $\vec{K}^+$  and total magnetic current  $\vec{L}^+$ ; on the inside surface, there are  $\vec{K}^-$  and  $\vec{L}^-$ . For an exterior problem, only  $\vec{K}^+$  and  $\vec{L}^+$  need to be found; for an interior problem, only  $\vec{K}^-$  and  $\vec{L}^-$  are necessary. A single formulation for solving both types of problems would appear to require finding all inside and outside currents therefore doubling the amount of work, but it turns out not to be the case because some of the currents are linear combinations of others. Furthermore, this formulation holds the key to answering the question posed above.

Since the shell is infinitesimally thin, from Maxwell equations the radiation to the outside and to the inside of the shell can both be given in terms of integrodifferential operators on the sum currents  $\vec{K} = \vec{K}^+ + \vec{K}^-$  and  $\vec{L} = \vec{L}^+ + \vec{L}^-$ . Note that the outside currents will not contribute to the radiation in the interior while the inside currents will not contribute to the radiation to the exterior of the shell. For simplicity in the description, we consider the exterior problem of electromagnetic scattering. By definition, the radiation is the difference between the total field and the incident field. On the surfaces of the shell, this definition links the incident  $\vec{E}$  and  $\vec{H}$  fields and the difference currents  $\vec{K}^+ - \vec{K}^-$  and  $\vec{L}^+ - \vec{L}^-$  to the sum currents. It is therefore natural to treat the difference currents and the sum currents as the four

unknowns to be solved instead of the inside and the outside currents.

The surface impedance on the outside surface of the shell normalized to the medium is denoted by  $Z^+$  and that on the inside surface is  $Z^-$ . They can be tensors if the impedances are anisotropic and may vary from point to point. By forming the sum impedance  $Z = (Z^+ + Z^-)/2$  and the difference impedance  $\Delta = (Z^+ - Z^-)/2$ , the impedance boundary conditions provide a set of relations between the difference and the sum currents. It turns out that the rank of  $Z$  determines how the unknown surface currents are solved. If  $Z$  is invertible, then the difference currents are linear combinations of the sum currents so that only the integrodifferential equations of the sum currents have to be solved. There are only two unknowns to be solved for both the exterior and the interior problems under this sum-difference current formulation. If  $Z$  is rank 0, then  $Z = 0$ ; the impedance boundary condition requires that  $\vec{L}$  be proportional to a  $90^\circ$  rotation of  $\Delta \vec{K}$ . The difference electric current is obtained from  $\vec{K}$  after the integrodifferential equation on  $\vec{K}$  is solved. This situation includes the case where  $Z^+ = Z^- = 0$  when the surface is perfectly conducting, thus the result answers the question about the transition of the equations from a problem of two variables to one which has only a single variable.

Instead of dealing with an impedance coated body, this thesis presents the sum-difference currents formulation of electromagnetic boundary value problems for the scattering of an infinitesimally thin surface for which both the inside and the outside currents are true unknowns to be found. Extension of this formulation to impedance coated bodies is then discussed.

This formulation preserves the duality nature of Maxwell equations and carries it over into an explicit specific algebraic form of the integrodifferential operators in the equations for the sum currents. Since, for a plane wave, a  $90^\circ$  rotation is equivalent to undergoing a duality transform, this explicit symmetry in the algebraic form of the operators enables us to deduce sufficient conditions for eliminating the on-axis backscattering of an anisotropic impedance coated scatterer having a  $90^\circ$  rotational symmetry.

The sum-difference currents formulation is utilized for solving the problem of

electromagnetic scattering from an anisotropically impedance coated tubular cylinder of finite length. The solution has been coded in FORTRAN and tested. Some interesting results are presented and discussed.

In this thesis, the time dependence  $e^{-i\omega t}$  is used.  $\vec{E}$  represents the electric field intensity divided by the intrinsic impedance of the medium,  $\sqrt{\mu/\epsilon}$ ; therefore it has the same unit as  $\vec{H}$  in amperes per meter. So are the electric and magnetic equivalent surface currents  $\vec{K}$  and  $\vec{L}$ .



## II. THE SUM-DIFFERENCE SURFACE CURRENT FORMULATION OF ELECTROMAGNETIC BOUNDARY-VALUE PROBLEMS

### A. STRATTON-CHU FIELD FORMULATION AND RADIATION

On an orientable, piecewise regular surface, whether open or closed, having a surface electric current density  $\vec{K}$  and a surface magnetic current density  $\vec{L}$ , we define the Stratton-Chu E-field formula as:

$$\begin{aligned} \vec{E}_{s-c}(\vec{r}, S, \vec{K}, \vec{L}) = & \frac{ik^2}{4\pi} \int_S \vec{K}(\vec{r}_o) G(\vec{r}-\vec{r}_o) da_o - \frac{i}{4\pi} \nabla \int_S \vec{K}(\vec{r}_o) \cdot \nabla_o G(\vec{r}-\vec{r}_o) da_o \\ & - \frac{k}{4\pi} \nabla \times \int_S \vec{L}(\vec{r}_o) G(\vec{r}-\vec{r}_o) da_o \end{aligned} \quad (2-1)$$

where  $\vec{r}$  is a point which is not on  $S$ ,  $k = \omega\sqrt{\mu_o\epsilon_o}$  and  $G(\vec{r}-\vec{r}_o) = \frac{e^{ik|\vec{r}-\vec{r}_o|}}{k|\vec{r}-\vec{r}_o|}$ , then the Stratton-Chu H-field formula can be defined as:

$$\begin{aligned} \vec{H}_{s-c}(\vec{r}, S, \vec{K}, \vec{L}) = & \vec{E}_{s-c}(\vec{r}, S, \vec{L}, -\vec{K}) \\ = & \frac{k}{4\pi} \nabla \times \int_S \vec{K}(\vec{r}_o) G(\vec{r}-\vec{r}_o) da_o + \frac{ik^2}{4\pi} \int_S \vec{L}(\vec{r}_o) G(\vec{r}-\vec{r}_o) da_o \\ & - \frac{i}{4\pi} \nabla \int_S \vec{L}(\vec{r}_o) \cdot \nabla_o G(\vec{r}-\vec{r}_o) da_o \end{aligned} \quad (2-2)$$

Note that if  $S$  is a closed surface and  $\vec{K}$  and  $\vec{L}$  are the actual total equivalent surface currents on  $S$ , then  $\vec{E}_{s-c}$  and  $\vec{H}_{s-c}$  are respectively the  $\vec{E}$  and  $\vec{H}$  fields at  $\vec{r}$  due to all sources inside  $S$  if  $\vec{r}$  is located outside  $S$  and vice versa. This is a direct consequence of Maxwell's equations [2] and under this circumstance, the Stratton-Chu formulae are equivalent to Maxwell's equations. On the other hand, unlike the Poynting theorem, the Stratton-Chu field formulae over an open surface  $S$  are but integrodifferential operators on the tangential vector

fields  $\vec{K}$  and  $\vec{L}$  over  $S$  without any special physical meaning attached.

To introduce equivalent surface currents on  $S$ , the direction of the unit normal vector  $\hat{n}$  on the surface has to be chosen. Adopting the terminology for a closed surface, we can assign one side of any orientable surface  $S$  as the "outside surface"  $S^+$ , albeit somewhat arbitrarily if  $S$  is not closed. The outward normal  $\hat{n}^+$  is the unit normal pointing out of this side of  $S$  and for simplicity, we call  $\hat{n}^+$  the normal of  $S$  and denote it by  $\hat{n}$ . The other side of the surface  $S$  is the "inside surface"  $S^-$ . At any point  $\vec{r}$  on  $S$ , the inward normal  $\hat{n}^-$  is  $-\hat{n}$ . As a convention, the fields and surface currents on  $S^+$  and  $S^-$  always carry the corresponding superscripts (Figure 2-1).

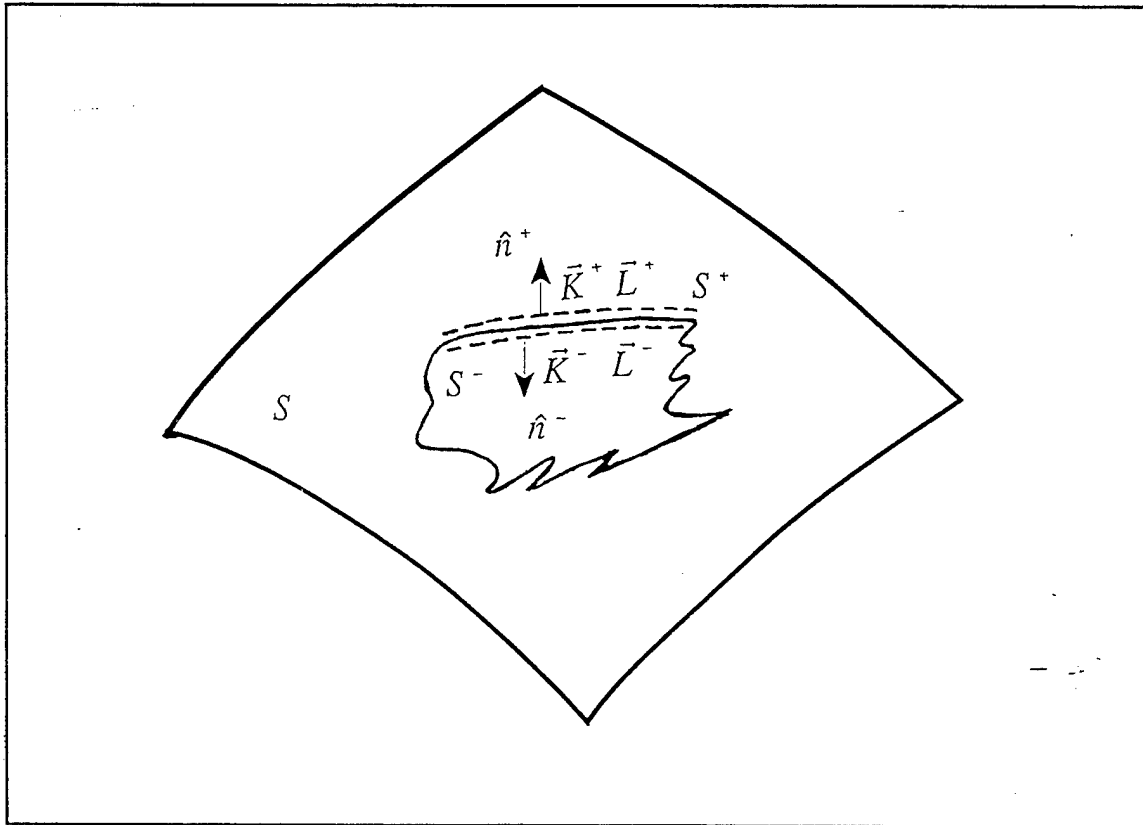


Figure 2-1. Outside and Inside Surfaces, Normals and the Equivalent Currents.

Each of the total surface currents  $\vec{K}^\pm$  and  $\vec{L}^\pm$  on  $S^\pm$  consists of two parts: the incident



current (with the additional superscript "inc") and the scattering current (with the additional superscript "sc") corresponding to the incident field and the scattered field on the particular side of the surface  $S$ :

$$\begin{aligned}\vec{K}^{\pm} &= \hat{n}^{\pm} \times \vec{H}^{\pm} = \hat{n}^{\pm} \times \vec{H}^{inc} + \hat{n}^{\pm} \times \vec{H}^{\pm,sc} \\ &= \vec{K}^{\pm,inc} + \vec{K}^{\pm,sc}\end{aligned}\quad (2-3)$$

$$\begin{aligned}\vec{L}^{\pm} &= \vec{E}^{\pm} \times \hat{n}^{\pm} = \vec{E}^{inc} \times \hat{n}^{\pm} + \vec{E}^{\pm,sc} \times \hat{n}^{\pm} \\ &= \vec{L}^{\pm,inc} + \vec{L}^{\pm,sc}\end{aligned}\quad (2-4)$$

Note that  $S$  is infinitesimally thin, hence  $\vec{H}^{+,inc} = \vec{H}^{-,inc} = \vec{H}^{inc}$  and  $\vec{E}^{+,inc} = \vec{E}^{-,inc} = \vec{E}^{inc}$  on  $S$  so that  $\vec{K}^{+,inc} = -\vec{K}^{-,inc}$  and  $\vec{L}^{+,inc} = -\vec{L}^{-,inc}$ . Therefore the sum currents  $\vec{K}$  and  $\vec{L}$  on  $S$  defined below are also the corresponding sums of the scattering currents only:

$$\begin{aligned}\vec{K} &= \vec{K}^{+} + \vec{K}^{-} = \vec{K}^{+,sc} + \vec{K}^{-,sc} \\ \vec{L} &= \vec{L}^{+} + \vec{L}^{-} = \vec{L}^{+,sc} + \vec{L}^{-,sc}\end{aligned}\quad (2-5)$$

Since the Stratton-Chu field formulae are linear operators on the surface currents, the radiated fields from surface currents on  $S$  are determined by the sum currents only:

$$\begin{aligned}\vec{E}^{sc}(\vec{r}) &= \vec{E}_{s-c}(\vec{r}, S^{+}, \vec{K}^{+}, \vec{L}^{+}) + \vec{E}_{s-c}(\vec{r}, S^{-}, \vec{K}^{-}, \vec{L}^{-}) = \vec{E}_{s-c}(\vec{r}, S, \vec{K}, \vec{L}) \\ \vec{H}^{sc}(\vec{r}) &= \vec{H}_{s-c}(\vec{r}, S, \vec{K}, \vec{L}) = \vec{E}_{s-c}(\vec{r}, S, \vec{L}, -\vec{K})\end{aligned}\quad (2-6)$$

## B. CONDITION ON THE CURRENTS IMPOSED BY MAXWELL'S EQUATIONS

As  $\vec{r}$  approaches  $\vec{r}^{\pm}$  on  $S^{\pm}$ , the tangential components (denoted by the subscript

"tan") of Eq. (2-6) provide four equations relating the incident fields and the total currents on both sides of  $S$  through the fact that the incident field is the difference between the total and the scattered field:

$$\vec{E}_{\text{tan}}^{\text{inc}} = \vec{E}_{\text{tan}}^+ - \vec{E}_{s-c,\text{tan}}(\vec{r}^+, S, \vec{K}, \vec{L}) \quad (2-7)$$

$$\vec{E}_{\text{tan}}^{\text{inc}} = \vec{E}_{\text{tan}}^- - \vec{E}_{s-c,\text{tan}}(\vec{r}^-, S, \vec{K}, \vec{L}) \quad (2-8)$$

$$\vec{H}_{\text{tan}}^{\text{inc}} = \vec{H}_{\text{tan}}^+ - \vec{H}_{s-c,\text{tan}}(\vec{r}^+, S, \vec{K}, \vec{L}) \quad (2-9)$$

$$\vec{H}_{\text{tan}}^{\text{inc}} = \vec{H}_{\text{tan}}^- - \vec{H}_{s-c,\text{tan}}(\vec{r}^-, S, \vec{K}, \vec{L}) \quad (2-10)$$

These four equations are not independent of each other. Because

$$\begin{aligned} \hat{n}^\pm \times (\vec{E}(\vec{r}^\pm) \times \hat{n}^\pm) &= \vec{E}_{\text{tan}}(\vec{r}^\pm) = \hat{n}^\pm \times \vec{L}^\pm \\ \hat{n}^\pm \times (\vec{H}(\vec{r}^\pm) \times \hat{n}^\pm) &= \vec{H}_{\text{tan}}(\vec{r}^\pm) = -\hat{n}^\pm \times \vec{K}^\pm \end{aligned} \quad (2-11)$$

the difference between Eqs. (2-7) and (2-8) trivially confirms the definition of the sum equivalent magnetic current while the difference between Eqs. (2-9) and (2-10) confirms the definition of the sum equivalent electric current as both can be deduced directly from Maxwell's equations. We choose to use the sum of Eqs. (2-7) and (2-8) and that of Eqs. (2-9) and (2-10) as the two independent linear combinations out of Eqs. (2-7) through (2-10) to link the incident fields to the total surface currents on  $S^\pm$  as dictated by Maxwell's equations:

$$\begin{aligned}
2\vec{E}_{\text{tan}}^{\text{inc}} &= \hat{n} \times (\vec{L}^+ - \vec{L}^-) - \left\{ \vec{E}_{s-c}(\vec{r}^+, S, \vec{K}, \vec{L}) + \vec{E}_{s-c}(\vec{r}^-, S, \vec{K}, \vec{L}) \right\} \\
&= \hat{n} \times (\vec{L}^+ - \vec{L}^-) + M\vec{K} - N\vec{L} \\
2\vec{H}_{\text{tan}}^{\text{inc}} &= -\hat{n} \times (\vec{K}^+ - \vec{K}^-) - \left\{ \vec{H}_{s-c}(\vec{r}^+, S, \vec{K}, \vec{L}) + \vec{H}_{s-c}(\vec{r}^-, S, \vec{K}, \vec{L}) \right\} \\
&= -\hat{n} \times (\vec{K}^+ - \vec{K}^-) + N\vec{K} + M\vec{L}
\end{aligned} \tag{2-12}$$

where  $M$  and  $N$  are linear integrodifferential operators on the tangential vector fields  $\vec{K}$  and  $\vec{L}$  over  $S$ .

Under any orthonormal coordinates  $(u, v)$  over  $S$  having  $\hat{u}$ ,  $\hat{v}$  as the unit basis vectors and with  $\hat{n} = \hat{u} \times \hat{v}$ , a tangential vector field  $\vec{A}$  over  $S$  can be written in matrix form as:

$$\vec{A} = \begin{bmatrix} A_u \\ A_v \end{bmatrix}. \text{ Then } \hat{n} \times \vec{A} = \begin{bmatrix} -A_v \\ A_u \end{bmatrix} = -i\sigma_2 \vec{A} \text{ where } \sigma_2 = \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix} \text{ is one of the Pauli spin}$$

matrices. Note that  $\sigma_2^2 = 1$ . Using these matrix notations, we can rewrite Eq. (2-12) in the following form:

$$\begin{bmatrix} 0 & i\sigma_2 \\ -i\sigma_2 & 0 \end{bmatrix} \begin{bmatrix} \vec{K}^+ - \vec{K}^- \\ \vec{L}^+ - \vec{L}^- \end{bmatrix} = \begin{bmatrix} M & -N \\ N & M \end{bmatrix} \begin{bmatrix} \vec{K} \\ \vec{L} \end{bmatrix} - 2 \begin{bmatrix} \vec{E}_{\text{tan}}^{\text{inc}} \\ \vec{H}_{\text{tan}}^{\text{inc}} \end{bmatrix} \tag{2-13}$$

### C. IMPEDANCE BOUNDARY CONDITION

Maxwell's equations alone cannot determine the electromagnetic fields completely. If  $S$  is an open surface, appropriate boundary condition which the fields satisfy on  $S$  must be specified. It is usually given in terms of the impedance boundary condition, a linear relation among the tangential components of the total  $\vec{E}$  and the total  $\vec{H}$  fields on  $S$ . If  $S$  is a closed surface, there are two possibilities: One is to specify the electric and magnetic properties of

the volume within  $S$  and require the fields to satisfy regularity conditions within  $S$  and be linked to the fields outside through boundary conditions across  $S$ ; another is to specify the impedance boundary condition on  $S^+$  for an exterior problem or on  $S^-$  for an interior problem. Note that an impedance boundary condition over a closed surface  $S$  completely separates the exterior from the interior of  $S$ . Therefore, the surface impedance on  $S^-$  can be arbitrary for an exterior problem while that on  $S^+$  can be arbitrary for an interior problem. In this thesis, normalized surface impedances  $Z^\pm$  are assumed to be specified on  $S^\pm$  whether  $S$  is an open or a closed surface. Note that an open surface  $S$  can be considered as bounded within the closed surface formed by joining  $S^+$  and  $S^-$ .

The impedance boundary conditions on  $S^\pm$  are defined by:

$$\hat{n}^\pm \times (\vec{E}^\pm \times \hat{n}^\pm) = Z^\pm (\hat{n}^\pm \times \vec{H}^\pm) \quad (2-14)$$

or equivalently, in terms of the total surface currents:

$$\hat{n}^\pm \times \vec{L}^\pm = Z^\pm \vec{K}^\pm \quad (2-15)$$

With the matrix notations for tangential vector fields over  $S$  in the orthonormal coordinate system  $(u, v)$  introduced before, we can consider  $Z^\pm$  as  $2 \times 2$  matrices and rewrite Eq. (2-15) in the form:

$$\mp i \sigma_2 \vec{L}^\pm = Z^\pm \vec{K}^\pm = \frac{1}{2} Z^\pm [\vec{K} \pm (\vec{K}^+ - \vec{K}^-)] \quad (2-16)$$

which can readily be recast into a relation among sum and difference currents:

$$\begin{bmatrix} -\Delta & -i \sigma_2 \\ Z & 0 \end{bmatrix} \begin{bmatrix} \vec{K}^+ - \vec{K}^- \\ \vec{L}^+ - \vec{L}^- \end{bmatrix} = \begin{bmatrix} Z & 0 \\ -\Delta & -i \sigma_2 \end{bmatrix} \begin{bmatrix} \vec{K} \\ \vec{L} \end{bmatrix} \quad (2-17)$$

with

$$Z = \frac{1}{2} (Z^+ + Z^-) \quad (2-18)$$

and

$$\Delta = \frac{1}{2} (Z^+ - Z^-) \quad (2-19)$$

Eqs. (2-13) and (2-17) are a set of four two-dimensional vector equations to be solved for the sum and difference equivalent electric and magnetic surface current densities on  $S$ .

#### D. ALGEBRA OF THE SUM-DIFFERENCE CURRENT EQUATIONS

The existence and uniqueness of a solution to either the exterior or the interior problem specified in terms of the impedance boundary condition have been well established [3]. Here we want to investigate how such a solution can be obtained from Eqs. (2-13) and (2-17). Clearly Eq. (2-17) defines uniquely the algebraic relationship between the difference and the sum currents if  $Z$  is invertible. For example, the difference currents can be expressed in terms of the sum currents:

$$\begin{bmatrix} \vec{K}^+ - \vec{K}^- \\ \vec{L}^+ - \vec{L}^- \end{bmatrix} = - \begin{bmatrix} 0 & i\sigma_2 \\ -i\sigma_2 & 0 \end{bmatrix} R \begin{bmatrix} \vec{K} \\ \vec{L} \end{bmatrix} \quad (2-20)$$

where

$$R = \begin{bmatrix} Z - \Delta Z^{-1} \Delta & -i\Delta Z^{-1} \sigma_2 \\ -i\sigma_2 Z^{-1} \Delta & \sigma_2 Z^{-1} \sigma_2 \end{bmatrix} \quad (2-21)$$

An equation for the sum currents is obtained by substituting Eq. (2-20) into Eq. (2-13):

$$\begin{bmatrix} M & -N \\ N & M \end{bmatrix} \begin{bmatrix} \vec{K} \\ \vec{L} \end{bmatrix} + R \begin{bmatrix} \vec{K} \\ \vec{L} \end{bmatrix} = 2 \begin{bmatrix} \vec{E}_{\tan}^{inc} \\ \vec{H}_{\tan}^{inc} \end{bmatrix} \quad (2-22)$$

which can be solved for  $\vec{K}$  and  $\vec{L}$ . Eq. (2-20) in turn enables us to compute the difference currents algebraically then split the sum and the difference currents into total currents on  $S^\pm$ .

If  $Z$  is not invertible, then the situation is more complicated.  $Z$  can either be of rank 0 when  $Z = 0$  or rank 1 when  $\det Z = 0$  but  $Z \neq 0$ . Eqs. (2-13) and (2-17) can be combined into an equation for the sum currents  $\vec{K}$  and  $\vec{L}$ :

$$\begin{bmatrix} 1 & i\Delta\sigma_2 \\ 0 & -iZ\sigma_2 \end{bmatrix} \begin{bmatrix} M & -N \\ N & M \end{bmatrix} \begin{bmatrix} \vec{K} \\ \vec{L} \end{bmatrix} + \begin{bmatrix} Z & 0 \\ -\Delta & -i\sigma_2 \end{bmatrix} \begin{bmatrix} \vec{K} \\ \vec{L} \end{bmatrix} = 2 \begin{bmatrix} 1 & i\Delta\sigma_2 \\ 0 & -iZ\sigma_2 \end{bmatrix} \begin{bmatrix} \vec{E}_{\tan}^{inc} \\ \vec{H}_{\tan}^{inc} \end{bmatrix} \quad (2-23)$$

When  $Z = 0$ , Eq. (2-17) gives the null relations  $\vec{L}^+ - \vec{L}^- = i\sigma_2\Delta(\vec{K}^+ - \vec{K}^-)$  and  $\vec{L} = i\sigma_2\Delta\vec{K}$  hence  $\vec{L}^\pm = i\sigma_2\Delta\vec{K}^\pm$ . Eq. (2-23) becomes one for  $\vec{K}$  only:

$$\begin{bmatrix} 1 & i\Delta\sigma_2 \end{bmatrix} \begin{bmatrix} M & -N \\ N & M \end{bmatrix} \begin{bmatrix} 1 \\ i\sigma_2\Delta \end{bmatrix} \vec{K} = 2 \begin{bmatrix} 1 & i\Delta\sigma_2 \end{bmatrix} \begin{bmatrix} \vec{E}_{\tan}^{inc} \\ \vec{H}_{\tan}^{inc} \end{bmatrix} \quad (2-24)$$

Eq. (2-13) has to be used to find the difference electric current:

$$\vec{K}^+ - \vec{K}^- = i\sigma_2[N + iM\sigma_2\Delta]\vec{K} - 2i\sigma_2\vec{H}_{\tan}^{inc} \quad (2-25)$$

Therefore,

$$\vec{K}^{\pm} = \frac{1}{2} \left\{ 1 \pm i\sigma_2 [N + iM\sigma_2\Delta] \right\} \vec{K} \mp i\sigma_2 \vec{H}_{\tan}^{inc} \quad (2-26)$$

Since the last term in Eq. (2-26) is  $\vec{K}^{\pm, inc}$ ,

$$\vec{K}^{\pm, sc} = \frac{1}{2} \left\{ 1 \pm i\sigma_2 [N + iM\sigma_2\Delta] \right\} \vec{K} \quad (2-27)$$

$\vec{L}^+$  and  $\vec{L}^-$  can be obtained algebraically by multiplying  $i\sigma_2\Delta$  to  $\vec{K}^+$  and  $\vec{K}^-$  respectively.

On the other hand, by Eq. (2-13),

$$\vec{L}^{\pm, sc} = \frac{1}{2} i\sigma_2 \left\{ \Delta \mp [M - iN\sigma_2\Delta] \right\} \vec{K} \quad (2-28)$$

Note that the  $Z = 0$  case includes the special situation  $Z^+ = Z^- = Z = \Delta = 0$  when both sides of  $S$  are perfectly conducting. Under this circumstance  $\vec{L} = \vec{L}^{\pm} = 0$  and the operator  $N$  is never involved.

When  $Z$  is rank 1,  $Z \neq 0$  but  $\det Z = 0$ . The right hand side of Eq. (2-17) provides one linear relation between the components of  $\vec{L} - i\sigma_2\Delta\vec{K}$  which can be used to reduce the four components of  $\vec{K}$  and  $\vec{L}$  as the unknown quantities in Eq. (2-23) to three so that the remaining three components can be solved. The left hand side of Eq. (2-17) assures that the same linear relationship between the components of  $\vec{L} - i\sigma_2\Delta\vec{K}$  exists between corresponding components of the difference currents. Eq. (2-13) again has to be invoked to compute three other linearly independent combinations of the components of the difference currents from the sum currents.

### E. CONSIDERATIONS FOR A CLOSED SURFACE

When  $S$  is a closed surface, the choice of  $Z^-$  can be arbitrary for an exterior problem such as scattering while the choice of  $Z^+$  is arbitrary for an interior problem. It is desirable to choose  $Z^- = -Z^+$  so that  $Z = 0$  and  $\Delta = Z^+ = -Z^-$ . Then we have  $\vec{L} = i \sigma_2 \Delta \vec{K}$  and only  $\vec{K}$  has to be computed. With such a choice, for an exterior problem,

$$\vec{K}^{+,sc} = \frac{1}{2}(1 - \sigma_2 M \sigma_2 Z^+ + i \sigma_2 N) \vec{K} \quad (2-29)$$

$$\vec{L}^{+,sc} = \frac{i \sigma_2}{2}(Z^+ + i N \sigma_2 Z^+ - M) \vec{K} \quad (2-30)$$

and for an interior problem:

$$\vec{K}^{-,sc} = \frac{1}{2}(1 - \sigma_2 M \sigma_2 Z^- - i \sigma_2 N) \vec{K} \quad (2-31)$$

$$\vec{L}^{-,sc} = \frac{i \sigma_2}{2}(M - Z^- + i N \sigma_2 Z^-) \vec{K} \quad (2-32)$$



### III. A THEOREM OF ANISOTROPIC ABSORBERS

#### A. AXIAL RADIATION FROM A SURFACE OF 90° ROTATIONAL SYMMETRY

The  $xy$ -plane cross section of a surface  $S$  having a 90° rotational symmetry around the  $z$ -axis is shown in Figure 3-1. Because of this symmetry,  $S$  can be decomposed into four non-overlapping congruent pieces  $S_1, S_2, S_3, S_4$  so that a 90° rotation will bring  $S_i$  into  $S_{i+1}$ .

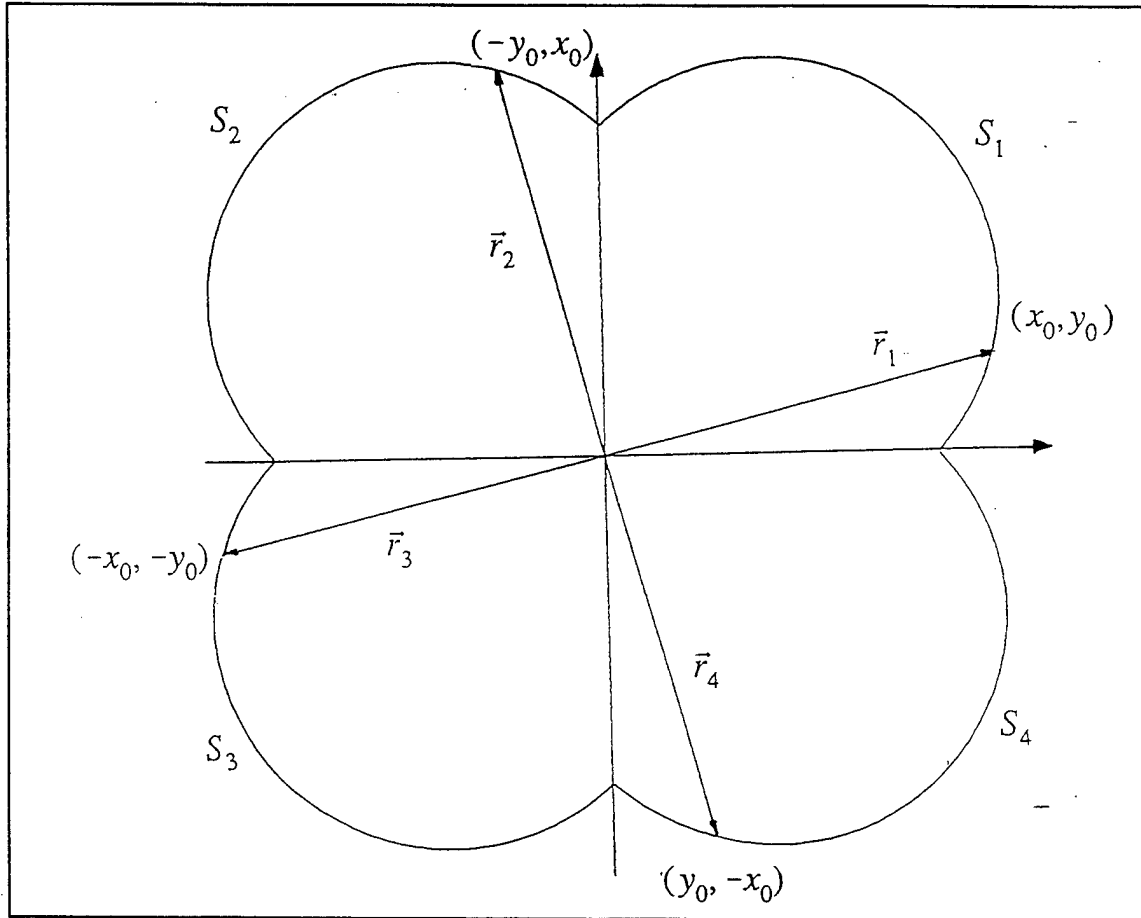


Figure 3-1. Cross Section of a Surface of 90-Degree Rotational Symmetry.

(These subscripts are considered as equal under modulo 4.) Therefore each piece  $S_i$  of  $S$  can

be parametrized in the same orthonormal coordinates  $(u, v)$ , with  $\hat{u} = \frac{\partial \vec{r}_i}{\partial u}$ ,  $\hat{v} = \frac{\partial \vec{r}_i}{\partial v}$  the

orthonormal basis vectors on  $S_i$ , as follows:

$$\begin{aligned}\vec{r}_1 &= (x_o(u, v), y_o(u, v), z_o(u, v)) \\ \vec{r}_2 &= (-y_o(u, v), x_o(u, v), z_o(u, v)) \\ \vec{r}_3 &= (-x_o(u, v), -y_o(u, v), z_o(u, v)) \\ \vec{r}_4 &= (y_o(u, v), -x_o(u, v), z_o(u, v))\end{aligned}\tag{3-1}$$

where  $\vec{r}_i \in S_i$ . As an example of a possible choice,  $u = \text{constant}$  and  $v = \text{constant}$  can be the lines of curvature of  $S_i$ .

In terms of the coordinates  $(u, v)$ , the sum surface current distributions on  $S_i$  are:

$$\begin{aligned}\vec{K}(\vec{r}_i) &= \vec{K}_i(u, v) \\ \vec{L}(\vec{r}_i) &= \vec{L}_i(u, v)\end{aligned}\tag{3-2}$$

Since for  $r \gg r_o$ ,

$$G(\vec{r}) \approx \frac{e^{ik|\vec{r}-\vec{r}_o|}}{kr}\tag{3-3}$$

$$\nabla G(\vec{r}) \approx ik\hat{r}G \approx -\nabla_o G(\vec{r})\tag{3-4}$$

the radiation from such current distributions at a distance  $r \gg \max |\vec{r}_1|$  along the positive z-axis is, from Eq. (2-6):

$$\begin{aligned}
\vec{E}^{sc}(\vec{r}) &= \vec{E}_{s-c}(\vec{r}, S, \vec{K}, \vec{L}) \\
&= \frac{ik}{4\pi r} \int_S \left\{ \hat{x} [K_x(\vec{r}_o) + L_y(\vec{r}_o)] + \hat{y} [K_y(\vec{r}_o) - L_x(\vec{r}_o)] \right\} e^{ik\sqrt{(z-z_o)^2 + x_o^2 + y_o^2}} da_o \\
&= \frac{ik}{4\pi r} \int \int_{S_1} \left\{ \hat{x} \sum_{i=1}^4 [K_{ix}(u, v) + L_{iy}(u, v)] \right. \\
&\quad \left. + \hat{y} \sum_{i=1}^4 [K_{iy}(u, v) - L_{ix}(u, v)] \right\} e^{ik\sqrt{(z-z_o)^2 + x_o^2 + y_o^2}} du dv
\end{aligned} \tag{3-5}$$

Note that this approximation is independent of the wavelength; it is applicable in regions closer to  $S$  than the usual Fresnel zone.

## B. CONDITION FOR VANISHING ON-AXIS BACKSCATTERING

Consider two situations when a linearly polarized plane wave of unit strength is incident on  $S$  along the  $z$ -axis from the positive direction: Situation 1, identified with the superscript (1) has the wave polarized in the  $x$ -direction while Situation 2, identified with the superscript (2), has the wave polarized in the  $y$ -direction. The incident fields are respectively:

$$\begin{aligned}
\vec{E}^{inc,(1)} &= \hat{x} e^{-ikz} \\
\vec{H}^{inc,(1)} &= -\hat{y} e^{-ikz}
\end{aligned} \tag{3-6}$$

$$\begin{aligned}
\vec{E}^{inc,(2)} &= \hat{y} e^{-ikz} \\
\vec{H}^{inc,(2)} &= \hat{x} e^{-ikz}
\end{aligned} \tag{3-7}$$

Note that, as seen from the positive  $z$ -axis, the incident wave in Situation 2 is that of Situation 1 rotated by  $90^\circ$  counterclockwise. Furthermore, Situation 2 can be obtained from Situation 1 through the duality transformation  $\vec{E}^{inc} \rightarrow \vec{H}^{inc}$ ,  $\vec{H}^{inc} \rightarrow -\vec{E}^{inc}$ . Therefore, for a plane wave, a  $90^\circ$  rotation is equivalent to undergoing the duality transform.

Because of the rotational symmetry of  $S$ , the currents excited on  $S_i$  under Situation 1 must appear on  $S_{i+1}$  under Situation 2. Therefore:

$$\begin{aligned}
K_{i+1,x}^{(2)}(u,v) &= -K_{i,y}^{(1)}(u,v) \\
K_{i+1,y}^{(2)}(u,v) &= K_{i,x}^{(1)}(u,v)
\end{aligned} \tag{3-8}$$

$$K_{i+1,z}^{(2)}(u,v) = K_{i,z}^{(1)}(u,v)$$

$$\begin{aligned}
L_{i+1,x}^{(2)}(u,v) &= -L_{i,y}^{(1)}(u,v) \\
L_{i+1,y}^{(2)}(u,v) &= L_{i,x}^{(1)}(u,v)
\end{aligned} \tag{3-9}$$

$$L_{i+1,z}^{(2)}(u,v) = L_{i,z}^{(1)}(u,v)$$

Assume that  $Z$  on  $S$  is invertible, the sum currents on  $S$  are determined by Eq. (2-22). The tangential components of the incident fields which appear on the right-hand-side of that equation under these two situations are:

$$\begin{bmatrix} \vec{E}_{\tan}^{inc,(1)} \\ \vec{H}_{\tan}^{inc,(1)} \end{bmatrix} = \begin{bmatrix} \hat{u} \cdot \hat{x} \\ \hat{v} \cdot \hat{x} \\ -\hat{u} \cdot \hat{y} \\ -\hat{v} \cdot \hat{y} \end{bmatrix} e^{-ikz} \tag{3-10}$$

$$\begin{bmatrix} \vec{E}_{\tan}^{inc,(2)} \\ \vec{H}_{\tan}^{inc,(2)} \end{bmatrix} = \begin{bmatrix} \hat{u} \cdot \hat{y} \\ \hat{v} \cdot \hat{y} \\ \hat{u} \cdot \hat{x} \\ \hat{v} \cdot \hat{x} \end{bmatrix} e^{-ikz} = \begin{bmatrix} 0 & -I \\ I & 0 \end{bmatrix} \begin{bmatrix} \vec{E}_{\tan}^{inc,(1)} \\ \vec{H}_{\tan}^{inc,(1)} \end{bmatrix} \tag{3-11}$$

where  $I$  is the  $2 \times 2$  identity matrix. Therefore,

$$\begin{bmatrix} M & -N \\ N & M \end{bmatrix} \begin{bmatrix} \vec{K}^{(1)} \\ \vec{L}^{(1)} \end{bmatrix} + R \begin{bmatrix} \vec{K}^{(1)} \\ \vec{L}^{(1)} \end{bmatrix} = 2 \begin{bmatrix} \vec{E}_{\tan}^{inc,(1)} \\ \vec{H}_{\tan}^{inc,(1)} \end{bmatrix} \quad (3-12)$$

$$\begin{bmatrix} M & -N \\ N & M \end{bmatrix} \begin{bmatrix} \vec{K}^{(2)} \\ \vec{L}^{(2)} \end{bmatrix} + R \begin{bmatrix} \vec{K}^{(2)} \\ \vec{L}^{(2)} \end{bmatrix} = 2 \begin{bmatrix} \vec{E}_{\tan}^{inc,(2)} \\ \vec{H}_{\tan}^{inc,(2)} \end{bmatrix} = 2 \begin{bmatrix} 0 & -I \\ I & 0 \end{bmatrix} \begin{bmatrix} \vec{E}_{\tan}^{inc,(1)} \\ \vec{H}_{\tan}^{inc,(1)} \end{bmatrix} \quad (3-13)$$

Since

$$\begin{bmatrix} 0 & -I \\ I & 0 \end{bmatrix} \begin{bmatrix} M & -N \\ N & M \end{bmatrix} = \begin{bmatrix} M & -N \\ N & M \end{bmatrix} \begin{bmatrix} 0 & -I \\ I & 0 \end{bmatrix} \quad (3-14)$$

it follows that if

$$\begin{bmatrix} 0 & -I \\ I & 0 \end{bmatrix} R = R \begin{bmatrix} 0 & -I \\ I & 0 \end{bmatrix} \quad (3-15)$$

we can multiply  $\begin{bmatrix} 0 & -I \\ I & 0 \end{bmatrix}$  to Eq. (3-12) to get:

$$\begin{bmatrix} M & -N \\ N & M \end{bmatrix} \begin{bmatrix} 0 & -I \\ I & 0 \end{bmatrix} \begin{bmatrix} \vec{K}^{(1)} \\ \vec{L}^{(1)} \end{bmatrix} + R \begin{bmatrix} 0 & -I \\ I & 0 \end{bmatrix} \begin{bmatrix} \vec{K}^{(1)} \\ \vec{L}^{(1)} \end{bmatrix} = 2 \begin{bmatrix} 0 & -I \\ I & 0 \end{bmatrix} \begin{bmatrix} \vec{E}_{\tan}^{inc,(1)} \\ \vec{H}_{\tan}^{inc,(1)} \end{bmatrix} \quad (3-16)$$

Therefore the excited surface currents in these two situations are related by:

$$\begin{bmatrix} \vec{K}^{(2)} \\ \vec{L}^{(2)} \end{bmatrix} = \begin{bmatrix} 0 & -I \\ I & 0 \end{bmatrix} \begin{bmatrix} \vec{K}^{(1)} \\ \vec{L}^{(1)} \end{bmatrix} = \begin{bmatrix} -\vec{L}^{(1)} \\ \vec{K}^{(1)} \end{bmatrix} \quad (3-17)$$

Combining this result with Eqs. (3-8) and (3-9), we have:

$$\begin{aligned}
K_{i+1,x}^{(2)}(u,v) &= -L_{i+1,x}^{(1)}(u,v) = -K_{i,y}^{(1)}(u,v) \\
K_{i+1,y}^{(2)}(u,v) &= -L_{i+1,y}^{(1)}(u,v) = K_{i,x}^{(1)}(u,v) \\
L_{i+1,x}^{(2)}(u,v) &= K_{i+1,x}^{(1)}(u,v) = -L_{i,y}^{(1)}(u,v) \\
L_{i+1,y}^{(2)}(u,v) &= K_{i+1,y}^{(1)}(u,v) = L_{i,x}^{(1)}(u,v)
\end{aligned} \tag{3-18}$$

so that

$$\sum_{i=1}^4 [K_{i,x}^{(1)}(u,v) + L_{i,y}^{(1)}(u,v)] = 0 \tag{3-19}$$

and

$$\sum_{i=1}^4 [K_{i,y}^{(1)}(u,v) - L_{i,x}^{(1)}(u,v)] = 0 \tag{3-20}$$

Hence, along the positive z-axis, from Eq (3-5),

$$\begin{aligned}
\bar{E}^{sc}(\vec{r}) &= \frac{ik}{4\pi r} \int \int_S \left\{ \hat{x} \sum_{i=1}^4 [K_{i,x}^{(1)}(u,v) + L_{i,y}^{(1)}(u,v)] \right. \\
&\quad \left. + \hat{y} \sum_{i=1}^4 [K_{i,y}^{(1)}(u,v) - L_{i,x}^{(1)}(u,v)] \right\} e^{ik\sqrt{(z-z_o)^2+x_o^2+y_o^2}} du dv \\
&= 0
\end{aligned} \tag{3-21}$$

and the backscattering from  $S$  along the positive z-direction must vanish if Eq. (3-15) is satisfied.

### C. IMPEDANCE MATRICES FOR ZERO ON-AXIS BACKSCATTERING

It can be verified that the matrix  $\begin{bmatrix} Z - \Delta Z^{-1} \Delta & -i \Delta Z^{-1} \sigma_2 \\ -i \sigma_2 Z^{-1} \Delta & \sigma_2 Z^{-1} \sigma_2 \end{bmatrix}$  commutes with  $\begin{bmatrix} 0 & -I \\ I & 0 \end{bmatrix}$

if and only if:

$$\sigma_2 Z^{-1} \Delta = -\Delta Z^{-1} \sigma_2 \quad (3-22)$$

$$Z - \sigma_2 Z^{-1} \sigma_2 = \Delta Z^{-1} \Delta \quad (3-23)$$

where both  $Z$  and  $\Delta$  are  $2 \times 2$  matrices. Under the assumption that the inverse of  $Z$  exists, we analyze Eqs. (3-22) and (3-23) as follows:

Because of the identity:

$$Z^{-1} = \frac{1}{\det Z} \sigma_2 Z^T \sigma_2 \quad (3-24)$$

and, by multiplying  $\sigma_2$  to both sides of Eq. (3-22):

$$Z^{-1} \Delta = -\sigma_2 \Delta Z^{-1} \sigma_2 \quad (3-25)$$

Eq. (3-23) can now be transformed to

$$\begin{aligned} Z &= -\Delta (\sigma_2 \Delta Z^{-1} \sigma_2) + \sigma_2 Z^{-1} \sigma_2 \\ &= -\Delta \sigma_2 \Delta \sigma_2 (\sigma_2 Z^{-1} \sigma_2) + \sigma_2 Z^{-1} \sigma_2 \\ &= \frac{1}{\det Z} [1 - (\Delta \sigma_2)^2] Z^T \end{aligned} \quad (3-26)$$

where

$$(\Delta \sigma_2)^2 = \Delta \sigma_2 \Delta \sigma_2 = \begin{bmatrix} \Delta_{11}\Delta_{22} - \Delta_{12}^2 & 0 \\ 0 & \Delta_{11}\Delta_{22} - \Delta_{21}^2 \end{bmatrix} \quad (3-27)$$

It is observed that Eq. (3-27) is greatly simplified if  $\Delta$  is symmetric. Therefore, in this thesis, we consider only the case when  $\Delta = \Delta^T$ . Then  $\Delta_{12} = \Delta_{21}$  so that:

$$(\Delta \sigma_2)^2 = (\det \Delta) I \quad (3-28)$$

From Eq. (3-26),

$$Z = \left( \frac{1 - \det \Delta}{\det Z} \right) Z^T \quad (3-29)$$

Eq. (3-29) can be satisfied only if  $\left( \frac{1 - \det \Delta}{\det Z} \right) = \pm 1$ . These two cases are:

Case I

$$Z = -Z^T = \begin{bmatrix} 0 & z_{12} \\ -z_{12} & 0 \end{bmatrix}, \quad z_{12} \neq 0 \quad (3-30)$$

$$\det \Delta = 1 + \det Z = 1 + z_{12}^2 \quad (3-31)$$

Case II

$$Z = Z^T \quad (3-32)$$



$$\det Z + \det \Delta = 1 \quad (3-33)$$

On the other hand, substituting Eq. (3-24) into Eq. (3-22) yields:

$$z_{11}(\Delta_{12} - \Delta_{21}) = (z_{12} - z_{21}) \Delta_{11} \quad (3-34)$$

$$z_{22}(\Delta_{12} - \Delta_{21}) = (z_{12} - z_{21}) \Delta_{22} \quad (3-35)$$

$$z_{11}\Delta_{22} + z_{22}\Delta_{11} = 2z_{21}\Delta_{12} = 2z_{12}\Delta_{21} \quad (3-36)$$

For Case 1, Eqs (3-34) and (3-35) require that  $\Delta_{11} = \Delta_{22} = 0$ , Eq. (3-36) requires that  $\Delta_{12} = \Delta_{21} = 0$ . Therefore  $\Delta = 0$ . From Eq (3-31),  $1 + z_{12}^2 = 0$ . Therefore  $z_{12} = \mp i$  so that  $Z^+ = Z^- = Z = \pm \sigma_2$ .

For Case II, Eqs. (3-34) and (3-35) are trivially satisfied. Eq (3-36) becomes:

$$z_{11}\Delta_{22} + z_{22}\Delta_{11} - 2z_{12}\Delta_{12} = 0 \quad (3-37)$$

Eq. (3-33) is explicitly:

$$z_{11}z_{22} - z_{12}^2 + \Delta_{11}\Delta_{22} - \Delta_{12}^2 = 1 \quad -(3-38)$$

The sum of Eq. (3-37) with Eq.(3-38) is:

$$(z_{11} + \Delta_{11})(z_{22} + \Delta_{22}) - (z_{12} + \Delta_{12})^2 = \det(Z + \Delta) = \det Z^+ = 1 \quad (3-39)$$

Subtracting Eq. (3-37) from Eq. (3-38):

$$(z_{11} - \Delta_{11})(z_{22} - \Delta_{22}) - (z_{12} - \Delta_{12})^2 = \det(Z - \Delta) = \det Z^- = 1 \quad (3-40)$$

In summary, two sufficient conditions to satisfy Eqs. (3-22) and (3-23) have been deduced under the assumptions that  $\Delta$  is symmetric and  $Z$  is invertible. The first one is:

$$Z^+ = Z^- = \pm \sigma_2 \quad (3-41)$$

The other, with both  $Z^+$  and  $Z^-$  symmetric, is:

$$\det Z^+ = \det Z^- = 1 \quad (3-42)$$

It should be noted that if  $S$  is a closed surface, the impedance boundary condition closes off the interior of the surface from its exterior. Therefore for the exterior problem,  $\det Z^+ = 1$  is sufficient to eliminate the on-axis backscattering from a body of  $90^\circ$  rotational symmetry. Furthermore,  $Z^+$  may vary with location. This is an extension of Weston's theory of isotropic absorbers [4].

#### IV. SCATTERING OF AN ANISOTROPICALLY COATED CYLINDER

In this chapter, the sum-difference surface current formulation developed in Chapter II is applied to the problem of scattering of an anisotropically coated tubular circular cylinder of finite length and negligible wall thickness. Due to the rotational symmetry, a Fourier series expansion can be utilized to reduce the variables of the problem to only the one along the axis of symmetry, chosen as the  $z$ -axis. The Fourier components  $M_n$ ,  $N_n$  of the operators  $M$  and  $N$  are deduced in terms of the Fourier components of  $G(\vec{r}-\vec{r}_0)$  and its partial derivatives. To solve the set of integrodifferential equations so obtained, the equations and the surface currents are both weighted and expanded over the Chebyshev polynomials. The resultant infinite system of linear equations are then truncated and inverted numerically.

##### A. GEOMETRY AND COORDINATE SYSTEM

Figure 4-1 shows the geometry and coordinate system of a tubular circular cylinder of radius  $a$  and length  $2h$ . The cylindrical coordinate system  $(\rho, \phi, z)$  is scaled so that the surface of the cylinder  $S$  is specified by  $\rho = 1$  and  $-1 \leq z \leq 1$ . The radial vector is thus given by:

$$\begin{aligned}\vec{r} &= a \rho \hat{\rho} + h z \hat{z} \\ &= a \rho (\cos \phi \hat{x} + \sin \phi \hat{y}) + h z \hat{z}\end{aligned}\tag{4-1}$$

To facilitate representing the tangent vectors over  $S$  in matrix form, we chose  $\hat{u} = \hat{\phi}$  and  $\hat{v} = \hat{z}$  as the orthonormal basis vectors on  $S$ , so that  $\hat{n} = \hat{\rho}$  is the outward normal to  $S$ .

To properly classify the polarization of the incident wave, the rectangular coordinate system  $(x, y, z)$  is determined as follows: When a plane wave is not incident along the  $z$ -axis, the coordinates are chosen so that the wave is propagating in the  $zx$ -plane incident from the half-plane containing the positive  $x$ -axis. Axial incidences then are considered as the limiting cases as the direction of incidence approaches the positive or the negative  $z$ -axis from this half-plane. Therefore, even for axial incidence, a linearly polarized incident wave having its

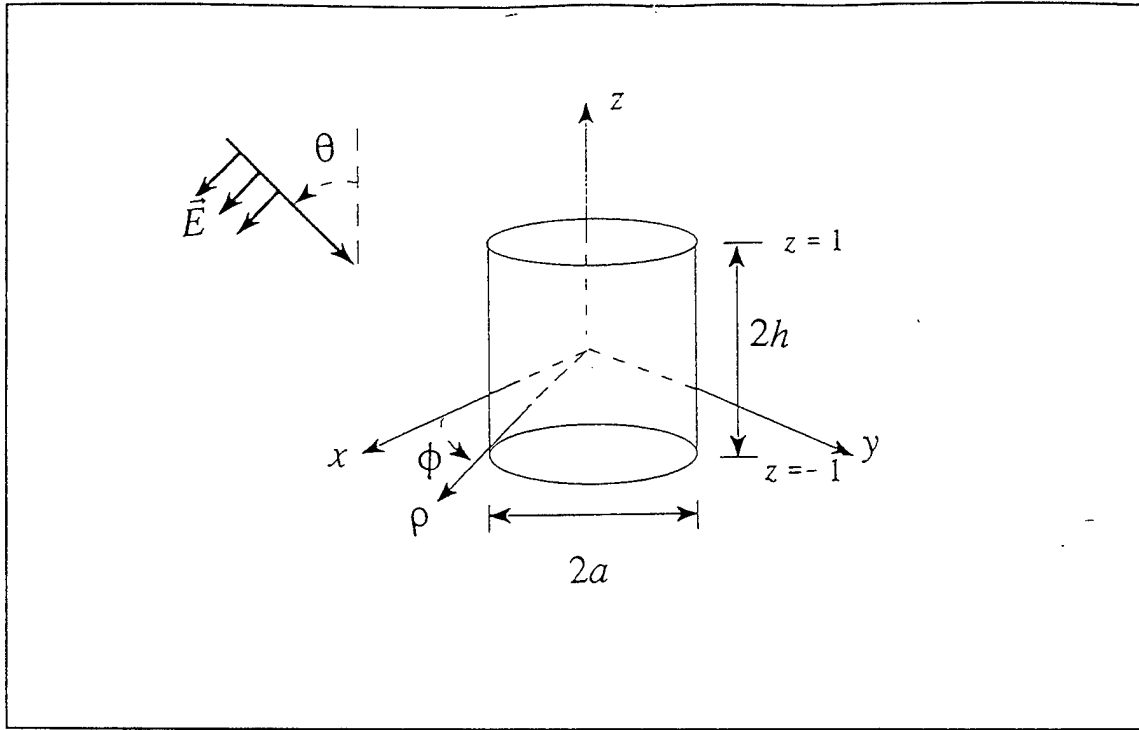


Figure 4-1. The Geometry and Coordinate System.

electric field intensity vector  $\vec{E}$  pointing in the  $y$ -direction is considered a TE wave while one having its  $\vec{E}$  vector in the  $zx$ -plane is considered a TM wave. In the spherical coordinate system  $(r, \theta, \phi)$ , the direction of propagation of the incident wave  $\hat{k}$  is given by  $\hat{k} = -\hat{z} \cos \theta_i - \hat{x} \sin \theta_i$  where the incident angle  $\theta_i$  varies over the range  $0 \leq \theta_i \leq \pi$ . For an incident plane wave of unit strength, the fields are:

TE - polariation:

$$\begin{aligned}\vec{E}^{inc} &= \hat{y} e^{i\vec{k} \cdot \vec{r}} \\ \vec{H}^{inc} &= \hat{k} \times \vec{E}^{inc} = (\hat{x} \cos \theta_i - \hat{z} \sin \theta_i) e^{i\vec{k} \cdot \vec{r}}\end{aligned}$$

TM - polarization:

$$\begin{aligned}\vec{H}^{inc} &= \hat{y} e^{i\vec{k} \cdot \vec{r}} \\ \vec{E}^{inc} &= \vec{H}^{inc} \times \hat{k} = -(\hat{x} \cos \theta_i - \hat{z} \sin \theta_i) e^{i\vec{k} \cdot \vec{r}}\end{aligned}$$

where  $\vec{k} = k \hat{k}$ . Note that  $\vec{k} \cdot \vec{r} = l_1 z \cos \theta_i + l_2 \rho \sin \theta_i \cos \phi$  where  $l_1 = kh$ , and  $l_2 = ka$ .

On the surfaces  $S$ , the tangential components of TE-polarized plane wave are:

$$\begin{aligned}E_\phi^{inc} &= \cos \phi e^{i\vec{k} \cdot \vec{r}} \\ H_\phi^{inc} &= -\cos \theta_i \sin \phi e^{i\vec{k} \cdot \vec{r}} \\ H_z^{inc} &= -\sin \theta_i e^{i\vec{k} \cdot \vec{r}}\end{aligned} \quad (4-1)$$

and the tangential components of TM-polarized plane wave are:

$$\begin{aligned}E_\phi^{inc} &= \cos \theta_i \sin \phi e^{i\vec{k} \cdot \vec{r}} \\ E_z^{inc} &= \sin \theta_i e^{i\vec{k} \cdot \vec{r}} \\ H_\phi^{inc} &= \cos \phi e^{i\vec{k} \cdot \vec{r}}\end{aligned} \quad (4-2)$$

## B. SCATTERED FIELDS

From Eq. (2-6), the scattered fields from the cylinder are given in terms of the sum equivalent electric current  $\vec{K}$  and the sum magnetic current  $\vec{L}$ :

$$\begin{aligned}\frac{4\pi}{l_1 l_2} \vec{E}^{sc}(\vec{r}) &= -\frac{1}{k} \nabla \times \int_{-1}^1 \int_0^{2\pi} \vec{L}(r_o) G(\vec{r} - \vec{r}_o) d\phi_o dz_o \\ &+ i \int_{-1}^1 \int_0^{2\pi} \vec{K}(r_o) G(\vec{r} - \vec{r}_o) d\phi_o dz_o \\ &- \frac{i}{k^2} \nabla \int_{-1}^1 \int_0^{2\pi} \vec{K}(r_o) \cdot \nabla_o G(\vec{r} - \vec{r}_o) d\phi_o dz_o\end{aligned} \quad (4-3)$$

and

$$\begin{aligned}
\frac{4\pi}{l_1 l_2} \vec{H}^{sc}(\vec{r}) &= \frac{1}{k} \nabla \times \int_{-1}^1 \int_0^{2\pi} \vec{K}(r_o) G(\vec{r}-\vec{r}_o) d\phi_o dz_o \\
&+ i \int_{-1}^1 \int_0^{2\pi} \vec{L}(r_o) G(\vec{r}-\vec{r}_o) d\phi_o dz_o \\
&- \frac{i}{k^2} \nabla \int_{-1}^1 \int_0^{2\pi} \vec{L}(r_o) \cdot \nabla_o G(\vec{r}-\vec{r}_o) d\phi_o dz_o
\end{aligned} \tag{4-4}$$

Their components in cylindrical coordinates are:

$$\begin{aligned}
\frac{4\pi}{l_1 l_2} E_\rho^{sc}(\vec{r}) &= \frac{1}{l_1} \frac{\partial}{\partial z} \int_{-1}^1 \int_0^{2\pi} (\hat{\Phi} \cdot \hat{\Phi}_o) L_\phi(\vec{r}_o) G(\vec{r}-\vec{r}_o) d\phi_o dz_o \\
&- \frac{1}{l_2 \rho} \frac{\partial}{\partial \phi} \int_{-1}^1 \int_0^{2\pi} L_z(\vec{r}_o) G(\vec{r}-\vec{r}_o) d\phi_o dz_o \\
&+ i \int_{-1}^1 \int_0^{2\pi} (\hat{\rho} \cdot \hat{\Phi}_o) K_\phi(\vec{r}_o) G(\vec{r}-\vec{r}_o) d\phi_o dz_o \\
&+ \frac{i}{l_2^2} \frac{\partial^2}{\partial \rho \partial \phi} \int_{-1}^1 \int_0^{2\pi} K_\phi(\vec{r}_o) G(\vec{r}-\vec{r}_o) d\phi_o dz_o \\
&+ \frac{i}{l_1 l_2} \frac{\partial^2}{\partial \rho \partial z} \int_{-1}^1 \int_0^{2\pi} K_z(\vec{r}_o) G(\vec{r}-\vec{r}_o) d\phi_o dz_o
\end{aligned} \tag{4-5}$$

$$\begin{aligned}
\frac{4\pi}{l_1 l_2} E_\phi^{sc}(\vec{r}) &= -\frac{1}{l_1} \frac{\partial}{\partial z} \int_{-1}^1 \int_0^{2\pi} (\hat{\rho} \cdot \hat{\Phi}_o) L_\phi(\vec{r}_o) G(\vec{r}-\vec{r}_o) d\phi_o dz_o \\
&+ \frac{1}{l_2} \frac{\partial}{\partial \rho} \int_{-1}^1 \int_0^{2\pi} L_z(\vec{r}_o) G(\vec{r}-\vec{r}_o) d\phi_o dz_o \\
&+ i \int_{-1}^1 \int_0^{2\pi} (\hat{\Phi} \cdot \hat{\Phi}_o) K_\phi(\vec{r}_o) G(\vec{r}-\vec{r}_o) d\phi_o dz_o \\
&+ \frac{i}{l_2^2 \rho} \frac{\partial^2}{\partial \phi^2} \int_{-1}^1 \int_0^{2\pi} K_\phi(\vec{r}_o) G(\vec{r}-\vec{r}_o) d\phi_o dz_o \\
&+ \frac{i}{l_1 l_2 \rho} \frac{\partial^2}{\partial \phi \partial z} \int_{-1}^1 \int_0^{2\pi} K_z(\vec{r}_o) G(\vec{r}-\vec{r}_o) d\phi_o dz_o
\end{aligned} \tag{4-6}$$

$$\begin{aligned}
\frac{4\pi}{l_1 l_2} E_z^{sc}(\vec{r}) = & -\frac{1}{l_2 \rho} \frac{\partial}{\partial \rho} \int_{-1}^1 \int_0^{2\pi} (\hat{\Phi} \cdot \hat{\Phi}_o) L_\phi(\vec{r}_o) G(\vec{r} - \vec{r}_o) d\Phi_o dz_o \\
& + \frac{1}{l_2 \rho} \frac{\partial}{\partial \Phi} \int_{-1}^1 \int_0^{2\pi} (\hat{\rho} \cdot \hat{\Phi}_o) L_\phi(\vec{r}_o) G(\vec{r} - \vec{r}_o) d\Phi_o dz_o \\
& + \frac{i}{l_1 l_2} \frac{\partial^2}{\partial z \partial \Phi} \int_{-1}^1 \int_0^{2\pi} K_\phi(\vec{r}_o) G(\vec{r} - \vec{r}_o) d\Phi_o dz_o \\
& + i \left( 1 + \frac{1}{l_1^2} \frac{\partial^2}{\partial z^2} \right) \int_{-1}^1 \int_0^{2\pi} K_z(\vec{r}_o) G(\vec{r} - \vec{r}_o) d\Phi_o dz_o
\end{aligned} \tag{4-7}$$

$$\begin{aligned}
\frac{4\pi}{l_1 l_2} H_\rho^{sc}(\vec{r}) = & -\frac{1}{l_1} \frac{\partial}{\partial z} \int_{-1}^1 \int_0^{2\pi} (\hat{\Phi} \cdot \hat{\Phi}_o) K_\phi(\vec{r}_o) G(\vec{r} - \vec{r}_o) d\Phi_o dz_o \\
& + \frac{1}{l_2 \rho} \frac{\partial}{\partial \Phi} \int_{-1}^1 \int_0^{2\pi} K_z(\vec{r}_o) G(\vec{r} - \vec{r}_o) d\Phi_o dz_o \\
& + i \int_{-1}^1 \int_0^{2\pi} (\hat{\rho} \cdot \hat{\Phi}_o) L_\phi(\vec{r}_o) G(\vec{r} - \vec{r}_o) d\Phi_o dz_o \\
& + \frac{i}{l_2^2} \frac{\partial^2}{\partial \rho \partial \Phi} \int_{-1}^1 \int_0^{2\pi} L_\phi(\vec{r}_o) G(\vec{r} - \vec{r}_o) d\Phi_o dz_o \\
& + \frac{i}{l_1 l_2} \frac{\partial^2}{\partial \rho \partial z} \int_{-1}^1 \int_0^{2\pi} L_z(\vec{r}_o) G(\vec{r} - \vec{r}_o) d\Phi_o dz_o
\end{aligned} \tag{4-8}$$

$$\begin{aligned}
\frac{4\pi}{l_1 l_2} H_\phi^{sc}(\vec{r}) = & \frac{1}{l_1} \frac{\partial}{\partial z} \int_{-1}^1 \int_0^{2\pi} (\hat{\rho} \cdot \hat{\Phi}_o) K_\phi(\vec{r}_o) G(\vec{r} - \vec{r}_o) d\Phi_o dz_o \\
& - \frac{1}{l_2} \frac{\partial}{\partial \rho} \int_{-1}^1 \int_0^{2\pi} K_z(\vec{r}_o) G(\vec{r} - \vec{r}_o) d\Phi_o dz_o \\
& + i \int_{-1}^1 \int_0^{2\pi} (\hat{\Phi} \cdot \hat{\Phi}_o) L_\phi(\vec{r}_o) G(\vec{r} - \vec{r}_o) d\Phi_o dz_o \\
& + \frac{i}{l_2^2 \rho} \frac{\partial^2}{\partial \Phi^2} \int_{-1}^1 \int_0^{2\pi} L_\phi(\vec{r}_o) G(\vec{r} - \vec{r}_o) d\Phi_o dz_o \\
& + \frac{i}{l_1 l_2 \rho} \frac{\partial^2}{\partial \Phi \partial z} \int_{-1}^1 \int_0^{2\pi} L_z(\vec{r}_o) G(\vec{r} - \vec{r}_o) d\Phi_o dz_o
\end{aligned} \tag{4-9}$$

$$\begin{aligned}
\frac{4\pi}{l_1 l_2} H_z^{sc}(\vec{r}) = & \frac{1}{l_2 \rho} \frac{\partial}{\partial \rho} \int_{-1}^1 \int_0^{2\pi} \rho (\hat{\phi} \cdot \hat{\phi}_o) K_\phi(\vec{r}_o) G(\vec{r} - \vec{r}_o) d\phi_o dz_o \\
& - \frac{1}{l_2 \rho} \frac{\partial}{\partial \phi} \int_{-1}^1 \int_0^{2\pi} (\hat{\rho} \cdot \hat{\phi}_o) K_\phi(\vec{r}_o) G(\vec{r} - \vec{r}_o) d\phi_o dz_o \\
& + \frac{i}{l_1 l_2} \frac{\partial^2}{\partial z \partial \phi} \int_{-1}^1 \int_0^{2\pi} L_\phi(\vec{r}_o) G(\vec{r} - \vec{r}_o) d\phi_o dz_o \\
& + i \left( 1 + \frac{1}{l_1^2} \frac{\partial^2}{\partial z^2} \right) \int_{-1}^1 \int_0^{2\pi} L_z(\vec{r}_o) G(\vec{r} - \vec{r}_o) d\phi_o dz_o
\end{aligned} \tag{4-10}$$

Note that in the above equations,

$$\hat{\rho} = \hat{\rho}_o \cos(\phi - \phi_o) + \hat{\phi}_o \sin(\phi - \phi_o) \tag{4-11}$$

$$\hat{\phi} = -\hat{\rho}_o \sin(\phi - \phi_o) + \hat{\phi}_o \cos(\phi - \phi_o) \tag{4-12}$$

Because of the rotational symmetry  $G(\vec{r} - \vec{r}_o)$  depends on  $\phi - \phi_o$  and Fourier series can be introduced to eliminate the variable  $\phi$ . Define the Fourier series expansion of a function  $f(\phi, z)$  by:

$$f(\phi, z) = \sum_{n=-\infty}^{\infty} e^{in\phi} f_n(z) \tag{4-13}$$

then

$$G(\vec{r} - \vec{r}_o) = \frac{e^{ik|\vec{r} - \vec{r}_o|}}{k|\vec{r} - \vec{r}_o|} = \sum_{n=-\infty}^{\infty} e^{in(\phi - \phi_o)} G_n(l_1 |z - z_o|, l_2, \rho) \tag{4-14}$$

and



$$G_n(l_1|z-z_o|, l_2, \rho) = \int_{-\pi}^{\pi} \frac{d\phi}{2\pi} e^{-in(\phi-\phi_o)} G(\vec{r}-\vec{r}_o) \quad (4-15)$$

Eqs. (4-5) to (4-10) become:

$$\begin{aligned} \frac{2}{l_1 l_2} E_{\rho n}^{sc}(\rho, z) &= \frac{1}{2l_1} \frac{\partial}{\partial z} \int_{-1}^1 L_{\phi n}(z_o) [G_{n-1} + G_{n+1}] dz_o \\ &\quad - \frac{in}{l_2 \rho} \int_{-1}^1 L_{zn}(z_o) G_n dz_o \\ &\quad + \frac{1}{2} \int_{-1}^1 K_{\phi n}(z_o) [G_{n-1} - G_{n+1}] dz_o - \frac{n}{l_2^2} \frac{\partial}{\partial \rho} \int_{-1}^1 K_{\phi n}(z_o) G_n dz_o \\ &\quad + \frac{i}{l_1 l_2} \frac{\partial}{\partial \rho} \int_{-1}^1 \left[ \frac{\partial}{\partial z_o} K_{zn}(z_o) \right] G_n dz_o \end{aligned} \quad (4-16)$$

$$\begin{aligned} \frac{2}{l_1 l_2} E_{\phi n}^{sc}(\rho, z) &= \frac{i}{2l_1} \frac{\partial}{\partial z} \int_{-1}^1 L_{\phi n}(z_o) [G_{n-1} - G_{n+1}] dz_o + \frac{1}{l_2} \frac{\partial}{\partial \rho} \int_{-1}^1 L_{zn}(z_o) G_n dz_o \\ &\quad + i \int_{-1}^1 K_{\phi n}(z_o) \left[ \frac{1}{2} (G_{n-1} + G_{n+1}) - \frac{n^2}{l_2^2 \rho} G_n \right] dz_o \\ &\quad - \frac{n}{l_1 l_2 \rho} \int_{-1}^1 \left[ \frac{\partial}{\partial z_o} K_{zn}(z_o) \right] G_n dz_o \end{aligned} \quad (4-17)$$

$$\begin{aligned} \frac{2}{l_1 l_2} E_{zn}^{sc}(\rho, z) &= \frac{1}{2l_2 \rho} \int_{-1}^1 L_{\phi n}(z_o) [(n-1)G_{n-1} - (n+1)G_{n+1}] dz_o \\ &\quad - \frac{1}{2l_2} \frac{\partial}{\partial \rho} \int_{-1}^1 L_{\phi n}(z_o) [G_{n-1} + G_{n+1}] dz_o \\ &\quad - \frac{n}{l_1 l_2} \frac{\partial}{\partial z} \int_{-1}^1 K_{\phi n}(z_o) G_n dz_o \\ &\quad + \frac{i}{l_1^2} \frac{\partial}{\partial z} \int_{-1}^1 \left[ \frac{\partial}{\partial z_o} K_{zn}(z_o) \right] G_n dz_o + i \int_{-1}^1 K_{zn}(z_o) G_n dz_o \end{aligned} \quad (4-18)$$

$$\begin{aligned}
\frac{2}{l_1 l_2} H_{\rho n}^{sc}(\rho, z) = & -\frac{1}{2l_1} \frac{\partial}{\partial z} \int_{-1}^1 K_{\phi n}(z_o) [G_{n-1} + G_{n+1}] dz_o \\
& + \frac{in}{l_2 \rho} \int_{-1}^1 K_{zn}(z_o) G_n dz_o \\
& + \frac{1}{2} \int_{-1}^1 L_{\phi n}(z_o) [G_{n-1} - G_{n+1}] dz_o - \frac{n}{l_2^2} \frac{\partial}{\partial \rho} \int_{-1}^1 L_{\phi n}(z_o) G_n dz_o \\
& + \frac{i}{l_1 l_2} \frac{\partial}{\partial \rho} \int_{-1}^1 \left[ \frac{\partial}{\partial z_o} L_{zn}(z_o) \right] G_n dz_o
\end{aligned} \tag{4-19}$$

$$\begin{aligned}
\frac{2}{l_1 l_2} H_{\phi n}^{sc}(\rho, z) = & -\frac{i}{2l_1} \frac{\partial}{\partial z} \int_{-1}^1 K_{\phi n}(z_o) [G_{n-1} - G_{n+1}] dz_o - \frac{1}{l_2} \frac{\partial}{\partial \rho} \int_{-1}^1 K_{zn}(z_o) G_n dz_o \\
& + i \int_{-1}^1 L_{\phi n}(z_o) \left[ \frac{1}{2} (G_{n-1} + G_{n+1}) - \frac{n^2}{l_2^2 \rho} G_n \right] dz_o \\
& - \frac{n}{l_1 l_2 \rho} \int_{-1}^1 \left[ \frac{\partial}{\partial z} L_{zn}(z_o) \right] G_n dz_o
\end{aligned} \tag{4-20}$$

$$\begin{aligned}
\frac{2}{l_1 l_2} H_{zn}^{sc}(\rho, z) = & -\frac{1}{2l_2 \rho} \int_{-1}^1 K_{\phi n}(z_o) [(n-1)G_{n-1} - (n+1)G_{n+1}] dz_o \\
& + \frac{1}{2l_2} \frac{\partial}{\partial \rho} \int_{-1}^1 K_{\phi n}(z_o) [G_{n-1} + G_{n+1}] dz_o \\
& - \frac{n}{l_1 l_2} \frac{\partial}{\partial z} \int_{-1}^1 L_{\phi n}(z_o) G_n dz_o \\
& + \frac{i}{l_1^2} \frac{\partial}{\partial z} \int_{-1}^1 \left[ \frac{\partial}{\partial z_o} L_{zn}(z_o) \right] G_n dz_o + i \int_{-1}^1 L_{zn}(z_o) G_n dz_o
\end{aligned} \tag{4-21}$$

Note that in Eqs. (4-16) to (4-21),  $G_n$  stands for  $G_n(l_1|z-z_o|, l_2, \rho)$ . In shifting the  $z$ -derivative to the current densities  $K_{zn}(z_o)$  and  $L_{zn}(z_o)$ , the fact that edge conditions [5] require that these components of the scattering currents vanish as  $|z_o|$  approach 1 from below is used.

As  $\rho \rightarrow 1^\pm$ , the operators  $M_n$  and  $N_n$  can be deduced from Eqs. (4-16) to (4-21):

$$\begin{aligned}
M_{n,11} &= -i l_1 l_2 \int_{-1}^1 dz_o \left[ \frac{1}{2} (G_{n-1} + G_{n+1}) - \frac{n^2}{l_2^2} G_n \right]_{\rho=1} \\
M_{n,12} &= n \int_{-1}^1 dz_o [G_n]_{\rho=1} \frac{\partial}{\partial z_o} \\
M_{n,21} &= n \frac{\partial}{\partial z} \int_{-1}^1 dz_o [G_n]_{\rho=1} \\
M_{n,22} &= -i l_1 l_2 \int_{-1}^1 dz_o \left[ [G_n]_{\rho=1} + \frac{1}{l_1^2} \frac{\partial}{\partial z} [G_n]_{\rho=1} \frac{\partial}{\partial z_o} \right]
\end{aligned} \tag{4-22}$$

$$\begin{aligned}
N_{n,11} &= \frac{i}{2} l_2 \frac{\partial}{\partial z} \int_{-1}^1 dz_o [G_{n-1} - G_{n+1}]_{\rho=1} \\
N_{n,12} &= \frac{1}{2} l_1 l_2 \int_{-1}^1 dz_o \frac{\partial}{\partial l_2} [G_n]_{\rho=1} \\
N_{n,21} &= \frac{l_1}{2} \int_{-1}^1 dz_o \left\{ [(n-1)G_{n-1} - (n+1)G_{n+1}]_{\rho=1} - \frac{1}{2} l_2 \frac{\partial}{\partial l_2} [G_{n-1} + G_{n+1}]_{\rho=1} \right\} \\
N_{n,22} &= 0
\end{aligned} \tag{4-23}$$

Note that:

$$\frac{i}{l_2} \left( \frac{\partial}{\partial \rho} \Big|_{\rho=1^-} + \frac{\partial}{\partial \rho} \Big|_{\rho=1^+} \right) G_n(l_1 |z - z_0|, l_2, \rho) = \frac{\partial}{\partial l_2} G_n(l_1 |z - z_0|, l_2, 1) \tag{4-24}$$

Assuming that  $Z$  is invertible, from Eq. (2-23), the equations for the sum currents are therefore:

$$\begin{bmatrix} M_n & -N_n \\ N_n & M_n \end{bmatrix} \begin{bmatrix} \vec{K}_n \\ \vec{L}_n \end{bmatrix} + R \begin{bmatrix} \vec{K}_n \\ \vec{L}_n \end{bmatrix} = 2 \begin{bmatrix} \vec{E}_{\tan,n}^{inc} \\ \vec{H}_{\tan,n}^{inc} \end{bmatrix} \tag{4-25}$$

where

$$R = \begin{bmatrix} Z - \Delta Z^{-1} \Delta & -i \Delta Z^{-1} \sigma_2 \\ -i \sigma_2 Z^{-1} \Delta & \sigma_2 Z^{-1} \sigma_2 \end{bmatrix} \quad (4-26)$$

and the vectors  $\vec{K}_n$ ,  $\vec{L}_n$ ,  $\vec{E}_{\tan,n}^{inc}$ ,  $\vec{L}_{\tan,n}^{inc}$  are two dimensional column matrix representations of the respective tangential vector fields on  $S$  over the orthonormal basis  $\hat{\phi}$ ,  $\hat{z}$ . The incident fields are, for TE and TM polarizations respectively:

TE:

$$\begin{aligned} E_{\phi,n}^{inc} &= (-i)^{n-1} J'_n(l_2 \sin \theta_i) e^{-il_1 z \cos \theta_i} \\ H_{\phi,n}^{inc} &= -\frac{n(-i)^n \cos \theta_i}{l_2 \sin \theta_i} J_n(l_2 \sin \theta_i) e^{-il_1 z \cos \theta_i} \\ H_{z,n}^{inc} &= -\sin \theta_i (-i)^{n-1} J_n(l_2 \sin \theta_i) e^{-il_1 z \cos \theta_i} \end{aligned} \quad (4-27)$$

TM:

$$\begin{aligned} E_{\phi,n}^{inc} &= \frac{n(-i)^n \cos \theta_i}{l_2 \sin \theta_i} J_n(l_2 \sin \theta_i) e^{-il_1 z \cos \theta_i} \\ E_{z,n}^{inc} &= \sin \theta_i (-i)^n J_n(l_2 \sin \theta_i) e^{-il_1 z \cos \theta_i} \\ H_{\phi,n}^{inc} &= (-i)^{n-1} J'_n(l_2 \sin \theta_i) e^{-il_1 z \cos \theta_i} \end{aligned} \quad (4-28)$$

### C. TRANSFORM TO SYSTEM OF LINEAR EQUATIONS

Since the surface current components  $K_\phi(\phi, z_o) = O(1 - z_o^2)^{-1/2}$  and  $K_z(\phi, z_o) = O(1 - z_o^2)^{1/2}$  as  $|z_o| \rightarrow 1^-$ , representations of  $K_\phi(z_o)$  and  $\frac{d}{dz_o} K_z(z_o)$  in Chebyshev

polynomials of the first kind combined with the weighting factor conform to the proper edge behavior of the currents:

$$\begin{aligned}
K_{\phi,n}(z_o) &= \frac{1}{\pi \sin \nu} \sum_{q=0}^{\infty} K_{\phi,n}^q T_p(z_o) \\
&= \frac{1}{\pi \sin \nu} \sum_{q=0}^{\infty} K_{\phi,n}^q \cos q\nu \\
K_{z,n}(z_o) &= \frac{1}{\pi} \sum_{q=0}^{\infty} K_{z,n}^q \sin(q+1)\nu
\end{aligned} \tag{4-29}$$

where  $T_p(z_o)$  is the Chebyshev polynomials of the first kind and  $z_o = \cos \nu$ ,  $-1 \leq z_o \leq 1$ .

Similarly,

$$\begin{aligned}
L_{\phi,n}(z_o) &= \frac{1}{\pi \sin \nu} \sum_{q=0}^{\infty} L_{\phi,n}^q \cos q\nu \\
L_{z,n}(z_o) &= \frac{1}{\pi} \sum_{q=0}^{\infty} L_{z,n}^q \sin(q+1)\nu
\end{aligned} \tag{4-30}$$

For an invertible  $Z$ , the coefficients in the above equations are to be determined from Eq. (4-23). To make use of the orthogonal property of the Chebyshev polynomials, the factor  $\sin \nu \sin(p+1)\nu$  for  $p \geq 0$  is multiplied to both sides of Eq. (4-23) before an integration over the range of  $\nu$  is carried out. The results are described term by term in the subsection to follow. This procedure creates an infinite system of linear equations to be solved numerically after it is truncated at an appropriate order determined by the electrical size of the cylinder.

### 1. Incident Fields

$$\begin{bmatrix} \vec{E}_{\tan,n}^{inc,p} \\ \vec{H}_{\tan,n}^{inc,p} \end{bmatrix} = \frac{2}{p+1} \int_0^\pi \frac{d\nu}{\pi} \sin \nu \sin(p+1)\nu \begin{bmatrix} \vec{E}_{\tan,n}^{inc} \\ \vec{H}_{\tan,n}^{inc} \end{bmatrix} \tag{4-31}$$

TE:

$$\begin{aligned}
E_{\phi,n}^{inc,p} &= (-i)^{n+p-1} \left( J_{p-1}(l_1 \cos \theta_i) + J_{p+1}(l_1 \cos \theta_i) \right) J'_n(l_2 \sin \theta_i) \\
H_{\phi,n}^{inc,p} &= -\frac{2n(-i)^{n+p}}{l_1 l_2 \sin \theta_i} J_{p+1}(l_1 \cos \theta_i) J_n(l_2 \sin \theta_i) \\
H_{z,n}^{inc,p} &= -(-i)^{n+p} \sin \theta_i \left( J_{p-1}(l_1 \cos \theta_i) + J_{p+1}(l_1 \cos \theta_i) \right) J_n(l_2 \sin \theta_i)
\end{aligned} \tag{4-32}$$

TM:

$$\begin{aligned}
E_{\phi,n}^{inc,p} &= \frac{2n(-i)^{n+p}}{l_1 l_2 \sin \theta_i} J_{p+1}(l_1 \cos \theta_i) J_n(l_2 \sin \theta_i) \\
E_{z,n}^{inc,p} &= (-i)^{n+p} \sin \theta_i \left( J_{p-1}(l_1 \cos \theta_i) + J_{p+1}(l_1 \cos \theta_i) \right) J_n(l_2 \sin \theta_i) \\
H_{\phi,n}^{inc,p} &= (-i)^{n+p-1} \left( J_{p-1}(l_1 \cos \theta_i) + J_{p+1}(l_1 \cos \theta_i) \right) J'_n(l_2 \sin \theta_i)
\end{aligned} \tag{4-33}$$

where  $J'(\bullet)$  is a derivative with respect to the argument. Note that as  $\theta_i$  approaches 0 or  $\pi$ , only  $n = \pm 1$  terms are nonzero. Hence only  $n = \pm 1$  currents exist. For axial incident when  $\theta_i = 0$ :

TE:

$$\begin{aligned}
E_{\phi,1}^{inc,p} &= \frac{(-i)^p}{l_1} J_{p+1}(l_1) = E_{\phi,-1}^{inc,p} \\
H_{\phi,1}^{inc,p} &= -\frac{(-i)^{p+1}}{l_1} J_{p+1}(l_1) = -H_{\phi,-1}^{inc,p}
\end{aligned} \tag{4-34}$$

TM:

$$\begin{aligned}
E_{\phi,1}^{inc,p} &= \frac{(-i)^{p+1}}{l_1} J_{p+1}(l_1) = -E_{\phi,-1}^{inc,p} \\
H_{\phi,1}^{inc,p} &= \frac{(-i)^p}{l_1} J_{p+1}(l_1) = H_{\phi,-1}^{inc,p}
\end{aligned} \tag{4-35}$$

## 2. The $R$ - Matrix Term

$$\begin{aligned}
 & \frac{2}{p+1} \int_0^\pi \frac{dv}{\pi} \sin v \sin(p+1)v K_{\phi n}(\cos v) \\
 &= \frac{2}{(p+1)\pi^2} \sum_{q=0}^{\infty} K_{\phi, n}^q \int_0^\pi dv \sin(p+1)v \cos qv \\
 &= \sum_{q=0}^{\infty} A_{\phi}^{p, q} K_{\phi, n}^q
 \end{aligned} \tag{4-36}$$

where

$$A_{\phi}^{p, q} = \begin{cases} 0 & p+q \text{ odd} \\ \frac{4}{\pi^2(p+q+1)(p-q+1)} & p+q \text{ even} \end{cases} \tag{4-37}$$

$$\begin{aligned}
 & \frac{2}{p+1} \int_0^\pi \frac{dv}{\pi} \sin v \sin(p+1)v K_{zn}(\cos v) \\
 &= \frac{2}{(p+1)\pi^2} \sum_{q=0}^{\infty} K_{z, n}^q \int_0^\pi dv \sin v \sin(p+1)v \sin(q+1)v \\
 &= \sum_{q=0}^{\infty} A_z^{p, q} K_{z, n}^q
 \end{aligned} \tag{4-38}$$

where

$$A_z^{p, q} = \begin{cases} 0 & p+q \text{ odd} \\ \frac{-8(q+1)}{\pi^2(p+q+1)(p-q+1)(p+q+3)(p-q-1)} & p+q \text{ even} \end{cases} \tag{4-39}$$

Therefore:

$$\begin{aligned}
\frac{2}{p+1} \int_0^\pi \frac{dv}{\pi} \sin v \sin(p+1)v R \begin{bmatrix} \vec{K}_n \\ \vec{L}_n \end{bmatrix} &= \sum_{q=0}^{\infty} R \begin{bmatrix} A_\phi^{p,q} & 0 & 0 & 0 \\ 0 & A_z^{p,q} & 0 & 0 \\ 0 & 0 & A_\phi^{p,q} & 0 \\ 0 & 0 & 0 & A_z^{p,q} \end{bmatrix} \begin{bmatrix} \vec{K}_n^q \\ \vec{L}_n^q \end{bmatrix} \\
&= \sum_{q=0}^{\infty} R^{p,q} \begin{bmatrix} \vec{K}_n^q \\ \vec{L}_n^q \end{bmatrix}
\end{aligned} \tag{4-40}$$

where  $R^{p,q}$  is a four-by-four matrix, given in terms of  $R$  by

$$\left. \begin{aligned} R_{i1}^{p,q} &= R_{i1} A_\phi^{p,q} \\ R_{i2}^{p,q} &= R_{i2} A_z^{p,q} \\ R_{i3}^{p,q} &= R_{i3} A_\phi^{p,q} \\ R_{i4}^{p,q} &= R_{i4} A_z^{p,q} \end{aligned} \right\} \text{ for } i = 1, 2, 3, 4 \tag{4-41}$$

Note that  $R_{ij}^{p,q} = 0$  if  $p+q$  is odd.

### 3. The $M_n, N_n$ Operators

Define the 4x4 matrix  $X_n^{p,q}$  by:

$$\frac{2}{p+1} \int_0^\pi \frac{dv}{\pi} \sin v \sin(p+1)v \begin{bmatrix} M_n & -N_n \\ N_n & M_n \end{bmatrix} \begin{bmatrix} \vec{K}_n \\ \vec{L}_n \end{bmatrix} = \sum_{q=0}^{\infty} X_n^{p,q} \begin{bmatrix} \vec{K}_n^q \\ \vec{L}_n^q \end{bmatrix} \tag{4-42}$$

$$\begin{aligned}
&\frac{2}{p+1} \int_0^\pi \frac{dv}{\pi} \sin v \sin(p+1)v M_{n,11} [K_{\phi,n}(z_o)] \\
&= \sum_{q=0}^{\infty} \frac{-il_1 l_2}{p+1} \int_0^\pi \frac{dv}{\pi} [\cos p v \cos(p+2)v] \int_0^\pi \frac{dv_o}{\pi} \cos q v_o \left[ \frac{1}{2} (G_{n-1} + G_{n+1}) - \frac{n^2}{l_2^2} G_n \right] K_{\phi,n}^q \\
&= \sum_{q=0}^{\infty} X_{n,11}^{p,q} K_{\phi,n}^q
\end{aligned}$$



and,

$$X_{n,11}^{p,q} = -\frac{il_1 l_2}{p+1} \left[ \frac{1}{2} (G_{n-1}^{p,q} - G_{n-1}^{p+2,q} + G_{n+1}^{p,q} - G_{n+1}^{p+2,q}) - \frac{n^2}{l_2^2} (G_n^{p,q} - G_n^{p+2,q}) \right] \quad (4-43)$$

$$\begin{aligned} & \frac{2}{p+1} \int_0^\pi \frac{dv}{\pi} \sin v \sin(p+1)v M_{n,21} [K_{\phi,n}(z_o)] \\ &= \sum_{q=0}^{\infty} \frac{-2n}{p+1} \int_0^\pi \frac{dv}{\pi} \sin(p+1)v \frac{\partial}{\partial v} \int_0^\pi \frac{dv_o}{\pi} \cos qv_o G_n K_{\phi,n}^q \\ &= \sum_{q=0}^{\infty} 2n \int_0^\pi \frac{dv}{\pi} \cos(p+1)v \int_0^\pi \frac{dv_o}{\pi} \cos qv_o G_n K_{\phi,n}^q \\ &= \sum_{q=0}^{\infty} X_{n,21}^{p,q} K_{\phi,n}^q \end{aligned}$$

and,

$$X_{n,21}^{p,q} = 2n G_n^{p+1,q} \quad (4-44)$$

$$\begin{aligned} & \frac{2}{p+1} \int_0^\pi \frac{dv}{\pi} \sin v \sin(p+1)v N_{n,11} [K_{\phi,n}(z_o)] \\ &= \sum_{q=0}^{\infty} \frac{-il_1}{p+1} \int_0^\pi \frac{dv}{\pi} \sin(p+1)v \frac{\partial}{\partial v} \int_0^\pi \frac{dv_o}{\pi} \cos qv_o [G_{n-1} - G_{n+1}] K_{\phi,n}^q \\ &= \sum_{q=0}^{\infty} X_{n,31}^{p,q} K_{\phi,n}^q \end{aligned}$$

and,

$$X_{n,31}^{p,q} = il_2 [G_{n-1}^{p+1,q} - G_{n+1}^{p+1,q}] \quad (4-45)$$

$$\begin{aligned}
& \frac{2}{p+1} \int_0^\pi \frac{dv}{\pi} \sin v \sin(p+1)v N_{n,21} [K_{\phi,n}(z_o)] \\
&= \sum_{q=0}^{\infty} \frac{l_1}{p+1} \int_0^\pi \frac{dv}{\pi} \sin v \sin(p+1)v \int_0^\pi \frac{dv_o}{\pi} \cos qv_o \\
& \quad \left[ (n-1)G_{n-1} - (n+1)G_{n+1} - \frac{l_2}{2} \frac{\partial}{\partial l_2} (G_{n-1} + G_{n+1}) \right] K_{\phi,n}^q \\
&= \sum_{q=0}^{\infty} X_{n,41}^{p,q} K_{\phi,n}^q
\end{aligned}$$

and,

$$\begin{aligned}
X_{n,41}^{p,q} = \frac{l_1}{2(p+1)} & \left[ (n-1)(G_{n-1}^{p,q} - G_{n-1}^{p+2,q}) - (n+1)(G_{n+1}^{p,q} - G_{n+1}^{p+2,q}) \right. \\
& \left. - \frac{l_2}{2} \frac{\partial}{\partial l_2} (G_{n-1}^{p,q} - G_{n-1}^{p+2,q} + G_{n+1}^{p,q} - G_{n+1}^{p+2,q}) \right] \quad (4-46)
\end{aligned}$$

$$\begin{aligned}
& \frac{2}{p+1} \int_0^\pi \frac{dv}{\pi} \sin v \sin(p+1)v M_{n,12} [K_{z,n}(z_o)] \\
&= \sum_{q=0}^{\infty} \frac{-2n}{p+1} \int_0^\pi \frac{dv}{\pi} \sin v \sin(p+1)v \int_0^\pi \frac{dv_o}{\pi} (q+1) \cos(q+1)v_o G_n K_{z,n}^q \\
&= \sum_{q=0}^{\infty} X_{n,12}^{p,q} K_{z,n}^q
\end{aligned}$$

and,

$$X_{n,12}^{p,q} = -\frac{n(q+1)}{p+1} [G_n^{p,q+1} - G_n^{p+2,q+1}] \quad (4-47)$$

$$\begin{aligned}
& \frac{2}{p+1} \int_0^\pi \frac{dv}{\pi} \sin v \sin(p+1)v M_{n,22} [K_{z,n}(z_o)] \\
&= \sum_{q=0}^{\infty} \frac{-2il_1l_2}{p+1} \left\{ \int_0^\pi \frac{dv}{\pi} \sin v \sin(p+1)v \int_0^\pi \frac{dv_o}{\pi} \sin v_o \sin(q+1)v_o G_n \right. \\
&\quad \left. + \frac{1}{l_1^2} \int_0^\pi \frac{dv}{\pi} \sin(p+1)v \frac{\partial}{\partial v} \int_0^\pi \frac{dv_o}{\pi} (q+1) \cos(q+1)v_o G_n \right\} K_{z,n}^q \\
&= \sum_{q=0}^{\infty} X_{n,22}^{p,q} K_{z,n}^q
\end{aligned}$$

and,

$$X_{n,22}^{p,q} = -\frac{il_1l_2}{2} \left[ \frac{1}{p+1} (G_n^{p,q} + G_n^{p+2,q+2} - G_n^{p,q+2} - G_n^{p+2,q}) - \frac{4(q+1)}{l_1^2} G_n^{p+1,q+1} \right] \quad (4-48)$$

$$\begin{aligned}
& \frac{2}{p+1} \int_0^\pi \frac{dv}{\pi} \sin v \sin(p+1)v N_{n,12} [K_{z,n}(z_o)] \\
&= \sum_{q=0}^{\infty} \frac{l_1l_2}{p+1} \int_0^\pi \frac{dv}{\pi} \sin v \sin(p+1)v \int_0^\pi \frac{dv_o}{\pi} \sin v_o \sin(q+1)v_o \left[ \frac{\partial}{\partial l_2} G_n \right] K_{z,n}^q \\
&= \sum_{q=0}^{\infty} X_{n,32}^{p,q} K_{z,n}^q
\end{aligned}$$

and,

$$X_{n,32}^{p,q} = \frac{l_1l_2}{4(p+1)} \frac{\partial}{\partial l_2} [G_n^{p,q} + G_n^{p+2,q+2} - G_n^{p+2,q} - G_n^{p,q+2}] \quad (4-49)$$

Note that, for  $n=0$ , the expressions simplify to:

$$\begin{aligned}
X_{o,11}^{p,q} &= -\frac{il_1l_2}{p+1}[G_1^{p,q} - G_1^{p+2,q}] \\
X_{o,41}^{p,q} &= -\frac{l_1}{p+1}[(G_1^{p,q} - G_1^{p+2,q}) + \frac{l_2}{2}\frac{\partial}{\partial l_2}(G_1^{p,q} - G_1^{p+2,q})] \\
X_{o,22}^{p,q} &= -\frac{il_1l_2}{2}\left[\frac{1}{p+1}(G_o^{p,q} + G_o^{p+2,q+2} - G_o^{p,q+2} - G_o^{p+2,q}) - \frac{4(q+1)}{l_1^2}G_o^{p+1,q+1}\right] \quad (4-50) \\
X_{o,32}^{p,q} &= \frac{l_1l_2}{4(p+1)}\frac{\partial}{\partial l_2}(G_o^{p,q} + G_o^{p+2,q+2} - G_o^{p,q+2} - G_o^{p+2,q}) \\
X_{o,21}^{p,q} &= X_{o,31}^{p,q} = X_{o,44}^{p,q} = X_{o,12}^{p,q} = 0
\end{aligned}$$

Also note that  $X_o^{p,q} = 0$  if  $p+q$  is odd.

From the symmetry of  $\begin{bmatrix} M_n & -N_n \\ N_n & M_n \end{bmatrix}$ , we can deduce that:

$$\begin{aligned}
X_{n,13}^{p,q} &= -X_{n,31}^{p,q} & X_{n,14}^{p,q} &= -X_{n,32}^{p,q} \\
X_{n,23}^{p,q} &= -X_{n,41}^{p,q} & X_{n,24}^{p,q} &= X_{n,42}^{p,q} = 0 \\
X_{n,33}^{p,q} &= X_{n,11}^{p,q} & X_{n,34}^{p,q} &= X_{n,12}^{p,q} \\
X_{n,43}^{p,q} &= X_{n,21}^{p,q} & X_{n,44}^{p,q} &= X_{n,22}^{p,q}
\end{aligned} \quad (4-51)$$

Note that for  $p+q$  odd,

$$X_{n,11}^{p,q} = X_{n,41}^{p,q} = X_{n,22}^{p,q} = X_{n,32}^{p,q} = X_{n,23}^{p,q} = X_{n,33}^{p,q} = X_{n,14}^{p,q} = X_{n,44}^{p,q} = 0 \quad (4-52)$$

and for  $p+q$  even,

$$X_{n,21}^{p,q} = X_{n,31}^{p,q} = X_{n,12}^{p,q} = X_{n,13}^{p,q} = X_{n,43}^{p,q} = X_{n,34}^{p,q} = 0 \quad (4-53)$$

The integrodifferential Eq. (4-25) is thus transformed into the infinite system of linear

equations of the unknown coefficients  $\begin{bmatrix} \vec{K}_n^q \\ \vec{L}_n^q \end{bmatrix}$ :

$$\sum_{q=0}^{\infty} [X_n^{p,q} + R^{p,q}] \begin{bmatrix} \vec{K}_n^q \\ \vec{L}_n^q \end{bmatrix} = 2 \begin{bmatrix} \vec{E}_{\tan,n}^{inc,p} \\ \vec{H}_{\tan,n}^{inc,p} \end{bmatrix} \quad (4-54)$$

which is to be solved numerically.

#### D. RADIATION IN THE FAR FIELD

In the far field, we can write Eq. (4-3) as:

$$\begin{aligned} \frac{4\pi}{l_1 l_2} \vec{E}^{sc}(\vec{r}) \approx & +i \int_{-1}^1 dz_o \int_0^{2\pi} d\phi_o [\vec{L}(\vec{r}_o) \times \hat{r}] G(\vec{r} - \vec{r}_o) \\ & + i \int_{-1}^1 dz_o \int_0^{2\pi} d\phi_o \left\{ \vec{K}(\vec{r}_o) - i\hat{r} [K_\phi(\vec{r}_o) \sin \theta \sin(\phi - \phi_o) \right. \\ & \left. + K_z(\vec{r}_o) \cos \theta] \right\} G(\vec{r} - \vec{r}_o) \end{aligned} \quad (4-55)$$

or equivalently,

$$\begin{aligned}
\frac{\vec{E}^{sc}(\vec{r})}{G(\vec{r})} &= \frac{il_1 l_2}{2} \int_{-1}^1 dz_o \int_o^{2\pi} \frac{d\phi_o}{2\pi} \left\{ \hat{\theta} [K_\phi \cos \theta \sin(\phi - \phi_o) - K_z \sin \theta + L_\phi \cos(\phi - \phi_o)] \right. \\
&\quad \left. + \hat{\phi} [K_\phi \cos(\phi - \phi_o) - L_\phi \cos \theta \sin(\phi - \phi_o) + L_z \sin \theta] \right\} e^{-i[l_1 z_o \cos \theta + l_2 \sin \theta \cos(\phi - \phi_o)]} \\
&= \frac{l_1 l_2}{2} \sum_{n=-\infty}^{\infty} (-i)^n e^{in\phi} \sum_{p=0}^{\infty} (-i)^{p+n} \\
&\quad \cdot \left\{ \hat{\theta} \left[ \left( i J_n(l_2 \sin \theta) \frac{n \cot \theta}{l_2} K_{\phi,n} - J'_n(l_2 \sin \theta) L_{\phi,n}^p \right) J_p(l_1 \cos \theta) \right. \right. \\
&\quad \left. \left. - \frac{i}{2} J_n(l_2 \sin \theta) \sin \theta K_{z,n}^p (J_p(l_1 \cos \theta) + J_{p+2}(l_1 \cos \theta)) \right] \right. \\
&\quad \left. - \hat{\phi} \left[ \left( J'_n(l_2 \sin \theta) K_{\phi,n}^p + i J_n(l_2 \sin \theta) \frac{n \cot \theta}{l_2} L_{\phi,n}^p \right) J_p(l_1 \cos \theta) \right. \right. \\
&\quad \left. \left. - \frac{i}{2} J_n(l_2 \sin \theta) \sin \theta L_{z,n}^p (J_p(l_1 \cos \theta) + J_{p+2}(l_1 \cos \theta)) \right] \right\} \quad (4-56)
\end{aligned}$$

As  $\theta \rightarrow 0$ , only the  $n = \pm 1$  terms are nonzero in this limit, and  $\hat{\theta} = \hat{\rho} = \hat{x} \cos \phi + \hat{y} \sin \phi$ ,  $\hat{\phi} = -\hat{x} \sin \phi + \hat{y} \cos \phi$ . We have  $\hat{\theta} \pm i\hat{\phi} = (\hat{x} \pm \hat{y})e^{\pm i\phi}$ :

$$\begin{aligned}
\frac{\vec{E}^{sc}(\vec{r})}{G(\vec{r})} &= \frac{l_1 l_2}{4} \sum_{p=0}^{\infty} (-i)^p \left\{ \hat{x} \left[ (K_{\phi,1}^p - K_{\phi,-1}^p) + i(L_{\phi,1}^p + L_{\phi,-1}^p) \right] \right. \\
&\quad \left. + i\hat{y} \left[ (K_{\phi,1}^p + K_{\phi,-1}^p) + i(L_{\phi,1}^p - L_{\phi,-1}^p) \right] \right\} J_p(l_1) \quad (4-57)
\end{aligned}$$

Similarly, as  $\theta \rightarrow \pi$ , only the  $n = \pm 1$  terms are nonzero.  $\hat{\theta} = -\hat{\rho} = -\hat{x} \cos \phi - \hat{y} \sin \phi$ ,  $\hat{\phi} = -\hat{x} \sin \phi + \hat{y} \cos \phi$ . We have  $\hat{\theta} \pm i\hat{\phi} = -(\hat{x} \mp \hat{y})e^{\pm i\phi}$ :

$$\begin{aligned}
\frac{\vec{E}^{sc}(\vec{r})}{G(\vec{r})} &= \frac{l_1 l_2}{4} \sum_{p=0}^{\infty} i^p \left\{ \hat{x} \left[ (K_{\phi,1}^p - K_{\phi,-1}^p) - i(L_{\phi,1}^p + L_{\phi,-1}^p) \right] \right. \\
&\quad \left. + \hat{y} \left[ i(K_{\phi,1}^p + K_{\phi,-1}^p) + (L_{\phi,1}^p - L_{\phi,-1}^p) \right] \right\} J_p(l_1) \quad (4-58)
\end{aligned}$$

## E. INSIDE AND OUTSIDE SURFACE CURRENTS

From Eq. (2-20) we have:

$$\begin{bmatrix} \vec{K}_n^{+p} - \vec{K}_n^{-p} \\ \vec{L}_n^{+p} - \vec{L}_n^{-p} \end{bmatrix} = - \begin{bmatrix} Z^{-1}\Delta & iZ^{-1}\sigma_2 \\ -i\sigma_2(Z - \Delta Z^{-1}\Delta) & -\sigma_2\Delta Z^{-1}\sigma_2 \end{bmatrix} \begin{bmatrix} \vec{K}_n^p \\ \vec{L}_n^p \end{bmatrix} \quad (4-59)$$

Therefore the following matrix equation is obtained:

$$\begin{bmatrix} \vec{K}_n^{\pm p} \\ \vec{L}_n^{\pm p} \end{bmatrix} = \frac{1}{2} \left\{ I \mp \begin{bmatrix} Z^{-1}\Delta & iZ^{-1}\sigma_2 \\ -i\sigma_2(Z - \Delta Z^{-1}\Delta) & -\sigma_2\Delta Z^{-1}\sigma_2 \end{bmatrix} \right\} \begin{bmatrix} \vec{K}_n^p \\ \vec{L}_n^p \end{bmatrix} \quad (4-60)$$





## V. COMPUTATION AND RESULTS

The solution to the problem of the scattering of an anisotropically coated tubular cylinder of finite length as formulated in the previous chapter has been coded in FORTRAN and tested. The program listings are included in the Appendix. Computation has been carried out on the 32-bit Sun SPARC Station running under the Unix operating system in the Electrical and Computer Engineering Department and the Computer Center. The evaluation of the double series expansion coefficients of the Green's function and its derivatives for greater values of  $ka$  and  $kh$  have also been done on the 64-bit Cray Y-MP EL98 in the Visualization Lab so that the accuracy of the results can be accessed.

The program accepts the geometry of the cylinder, the surface impedance matrices, the incident wave frequency, direction and its polarization in terms of TE, TM or some linear combination of the two. It computes the sum surface currents and the far field radiation in the directions specified, including the strength and the phase of each field component. It also breaks down the sum surface currents into the outside and the inside currents.

In this chapter, some interesting results of computation for the scattering of a tubular cylinder having the length-to-diameter ratio  $h/a$  of 4 or 6 are presented. All figures are attached at the end of this chapter. The wave is incident from the positive  $z$ -axis and is polarized in the  $\hat{y}$  direction.

### A. COMPARISON WITH EXPERIMENTAL DATA

For backscattering from a perfectly conducting tubular cylinder of a  $y$ -polarized plane wave incident from the positive  $z$ -axis, experimental data are available [6] over a frequency band of well beyond three octaves, with the circumference-to-wavelength ratio  $ka = 2\pi a/\lambda$  varied from 0.9448 to 3.3152. These data are measured with two sets of four cylinders each; one set having  $h/a = 4$ , the other with  $h/a = 6$ . Both data sets use the inner radii of the tubular cylinders as the parameter  $a$  [7]. The cylinder length-to-wavelength ratio  $2h/\lambda$  varies from 1.2030 to 4.2210 for the  $h/a = 4$  case and from 1.8045 to 6.3315 for the  $h/a$

= 6 case.

The experimental data are plotted against the results of theoretical computation. Figure 5-1 shows the backscattering from the set of cylinders having  $h/a = 4$ . Figure 5-2 shows those data from the set of cylinders with  $h/a = 6$ . The output of theoretical computation follows the measured data very closely. Note that the cutoff frequency of the dominant circular waveguide mode,  $TE_{11}$ , occurs at  $2h/\lambda = 2.344$  for the cylinders with  $h/a = 4$  and at  $2h/\lambda = 3.516$  for those with  $h/a = 6$ .

## B. NULL ON-AXIS BACKSCATTERING

Three different ways of coating a surface impedance  $Z_s$  on a tubular cylinder of  $h/a = 6$  are considered: Both on the outside surface and the inside surface; Only on the inside and leaving the outside surface perfectly conducting; Only on the outside and leaving the inside surface perfectly conducting. Here  $Z_s$  has the elements  $z_{s11} = 0.5$ ,  $z_{s22}$  varies from 0.1 to 5,  $z_{s12} = z_{s21} = 0$ . At a fixed frequency for which  $2h/\lambda = 3.194$ , slightly below the  $TE_{11}$  circular waveguide dominant mode cutoff of 3.516, the scattered fields are plotted in Figures 5-3 through 5-5. Figure 5-3 shows the results of computation for the case  $Z^+ = Z^- = Z_s = Z$ . As  $z_{s22}$  is varied through 2, the backscattering cross section vanishes as predicted in Chapter 3. Figure 5-4 shows the results for the case  $Z^+ = 0$  and  $Z^- = Z_s$ . As the impedance on the inside surface is increased, the excited field inside the tubular cylinder is dissipated and the backscattered power decreases exponentially. Figure 5-5 shows the results for the case  $Z^+ = Z_s$  and  $Z^- = 0$ . The backscattered power drops off rapidly at first as the impedance on the outside surface is increased. But the cross section quickly settles down to a fixed value presumably due to the current excited on the perfectly conducting inside surface of the cylinder.

Results of computation for the same configurations but at a higher frequency for which  $2h/\lambda = 4.865$ , above the  $TE_{11}$  circular waveguide dominant mode cutoff of 3.516, are plotted in Figures 5-6 through 5-8. Now that the incident wave can propagate through the cylinder in the dominant waveguide mode, the backscattering cross sections are about an

order of magnitude smaller than in previous cases. Figure 5-6 shows the results of computation for the case  $Z^+ = Z^- = Z_s = Z$ . Again the backscattering cross section vanishes as  $z_{22}$  is varied through 2. Figure 5-7 shows the results for the case  $Z^+ = 0$  and  $Z^- = Z_s$  while Figure 5-8 shows the results for the case  $Z^+ = Z_s$  and  $Z^- = 0$ . It appears that, above cutoff, the contribution to the backscattering cross section from the inside of the tubular cylinder is minimal: once the outside current is reduced by the increase in surface impedance, the backscattering cross section is reduced by more than 10 dB as shown in Figure 5-8. When the impedance coating is applied in the inside surface, the maximal reduction in the backscattering cross section is only about 1.2 dB.

### C. FREQUENCY DEPENDENCE

The axial backscattering of the two cases when the tubular cylinder is coated only on the inside or only on the outside with  $z_{s11} = 0.5$  and  $z_{s22} = 2$  are investigated for different frequencies with  $2h/\lambda$  varying from 0.1 to 7.5. Figure 5-9 shows the results of the case when only the inside surface is coated so that the backscattering is mainly due to the current excited on the outside surface. The reflection from the ends of the cylinder causes the fluctuation in backscattering cross section. Being waves in free space on the outside of the cylinder, the maxima and minima are evenly spaced with the minima occurring when  $2h/\lambda$  is a multiple of half integer. Figure 5-10 shows the results when only the outside surface is coated and the current on the inside surface dominates the contribution. The distinct feature in this case is that the backscattering cross section does not fluctuate with varying frequency below the waveguide mode cutoff. The incident wave is able to penetrate deeper into the cylinder with increasing frequency, resulting in a constantly rising strength of the backscattered field. Once beyond the circular waveguide mode cutoff, the wave can pass through the cylinder in the  $TE_{11}$  mode and the backscattering diminishes. The oscillation in the cross section at these higher frequencies represents the interference of reflected waves at the ends of the tube and the separation between maxima and minima should be determined by the guide wavelength at the particular frequency. These two situations should be

compared to Figure 5-11 which shows the results when both sides of the cylinder are perfectly conducting and the current can flow freely. The distinct notch in the cross section near the  $TE_{11}$  mode cutoff at  $2h/\lambda = 3.516$  and the subsequent faster variation in the cross section shows the combination of the two distinct features of Figures 5-9 and 5-10.

#### D. COMPUTATION ACCURACY

The main difficulty encountered in the computation is the evaluation of  $G_n^{p,q}(l_1, l_2)$  and its  $l_2$ -derivative by double power series sum when  $l_1$  becomes large. Computations for Figure 5-11, 5-13 and 5-15 use the  $G_n^{p,q}$  values evaluated with the Cray computer which has a 128-bit double precision number. Computations for Figures 5-12, 5-14 and 5-16 use the  $G_n^{p,q}$  values evaluated with the Sun SPARC Station which has a 64-bit double precision number. For  $2h/\lambda$  greater than about 6.2, the SPARC Station fails to provide accurate results.

Figures 5-13 and 5-15 are axial backscattering from a cylinder of  $h/a = 6$  coated with the impedances having the elements  $z_{11}^+ = z_{22}^- = 0.5$ ,  $z_{22}^+ = z_{11}^- = 0.4$ ,  $z_{12}^+ = z_{21}^+ = z_{12}^- = z_{21}^- = 0.3$ . Figure 5-13 shows the co-polarized backscattered field while Figure 5-15 shows the cross-polarized backscattering.

Cylinder	$2h(\text{cm})$	$2a^+$	$2a^-$
1	3.566	0.9525	0.8915
2	4.796	1.27	1.199
3	6.064	1.588	1.516
4	7.396	1.908	1.849

Axial backscattering (perfectly conducting cylinder,  $h/a = 4$ )

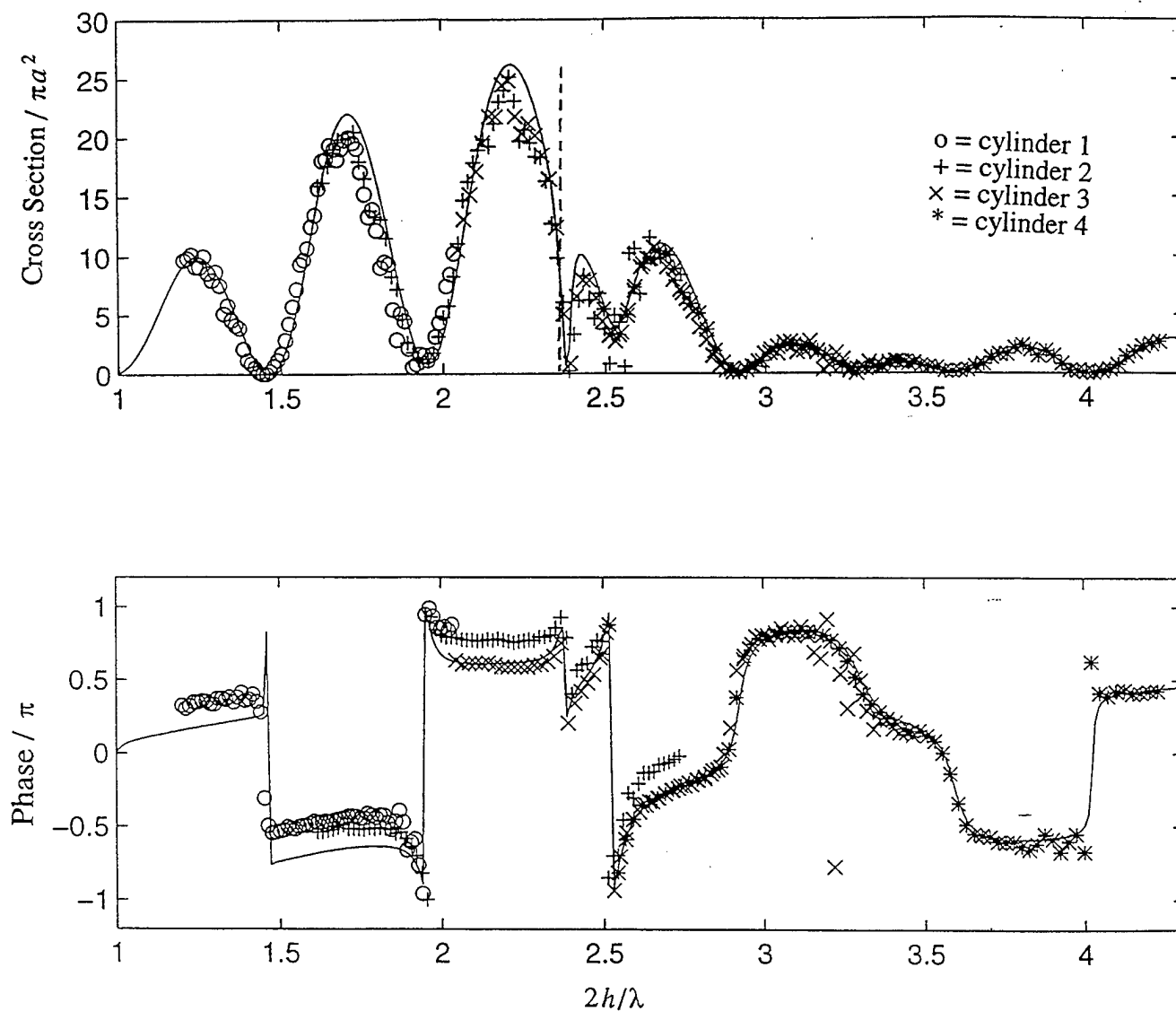


Figure 5-1.

Cylinder	$2h(\text{cm})$	$2a^+$	$2a^-$
1	5.394	0.9525	0.8915
2	7.193	1.270	1.199
3	9.098	1.588	1.516
4	11.09	1.905	1.849

Axial backscattering (perfectly conducting cylinder,  $h/a = 6$ )

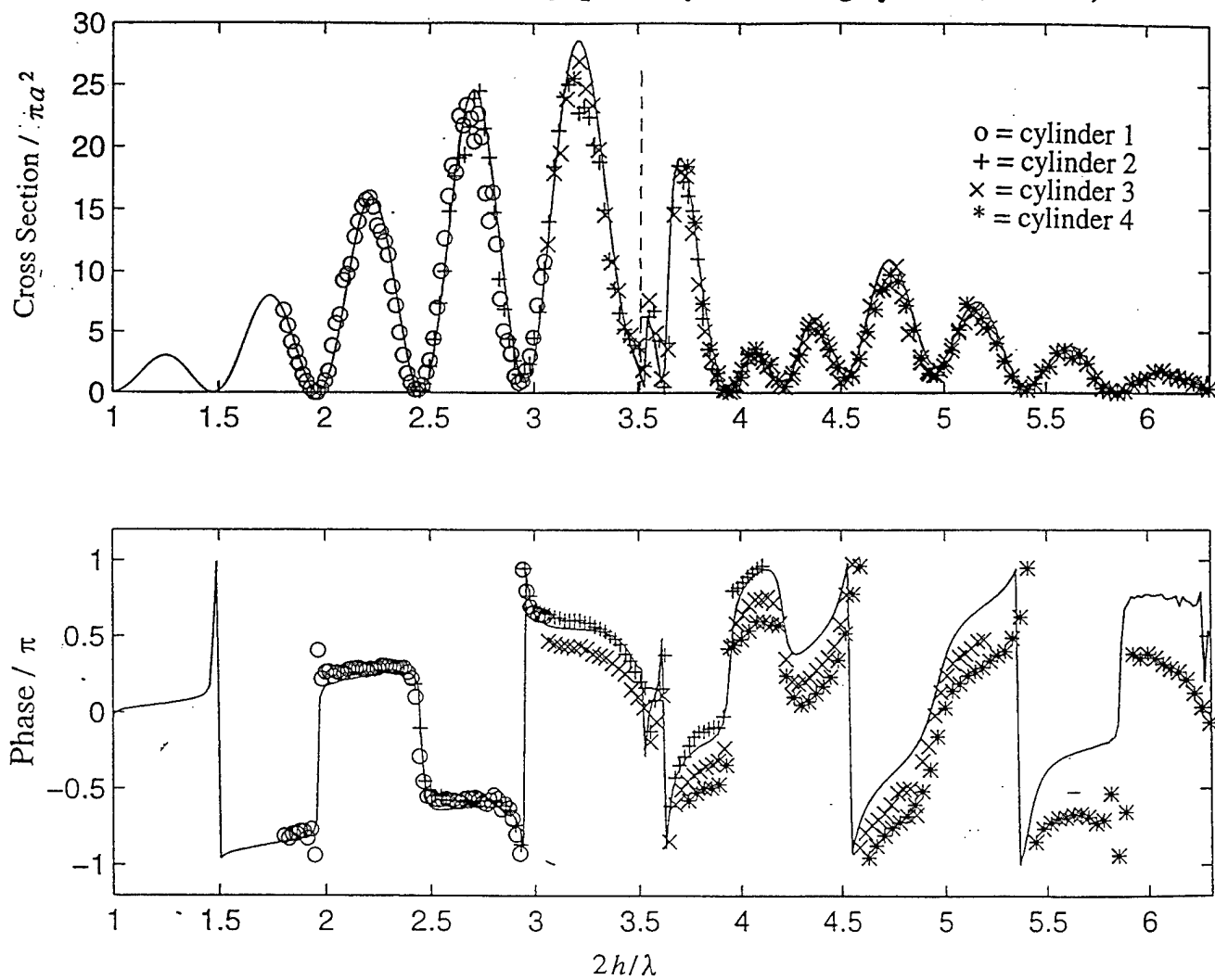


Figure 5-2.

$$Z^+ = Z^- = Z_s = \begin{bmatrix} 0.5 & 0 \\ 0 & z_{s22} \end{bmatrix}$$

Axial backscattering ( $h/a = 6$ ,  $2h/\lambda = 3.194$ )

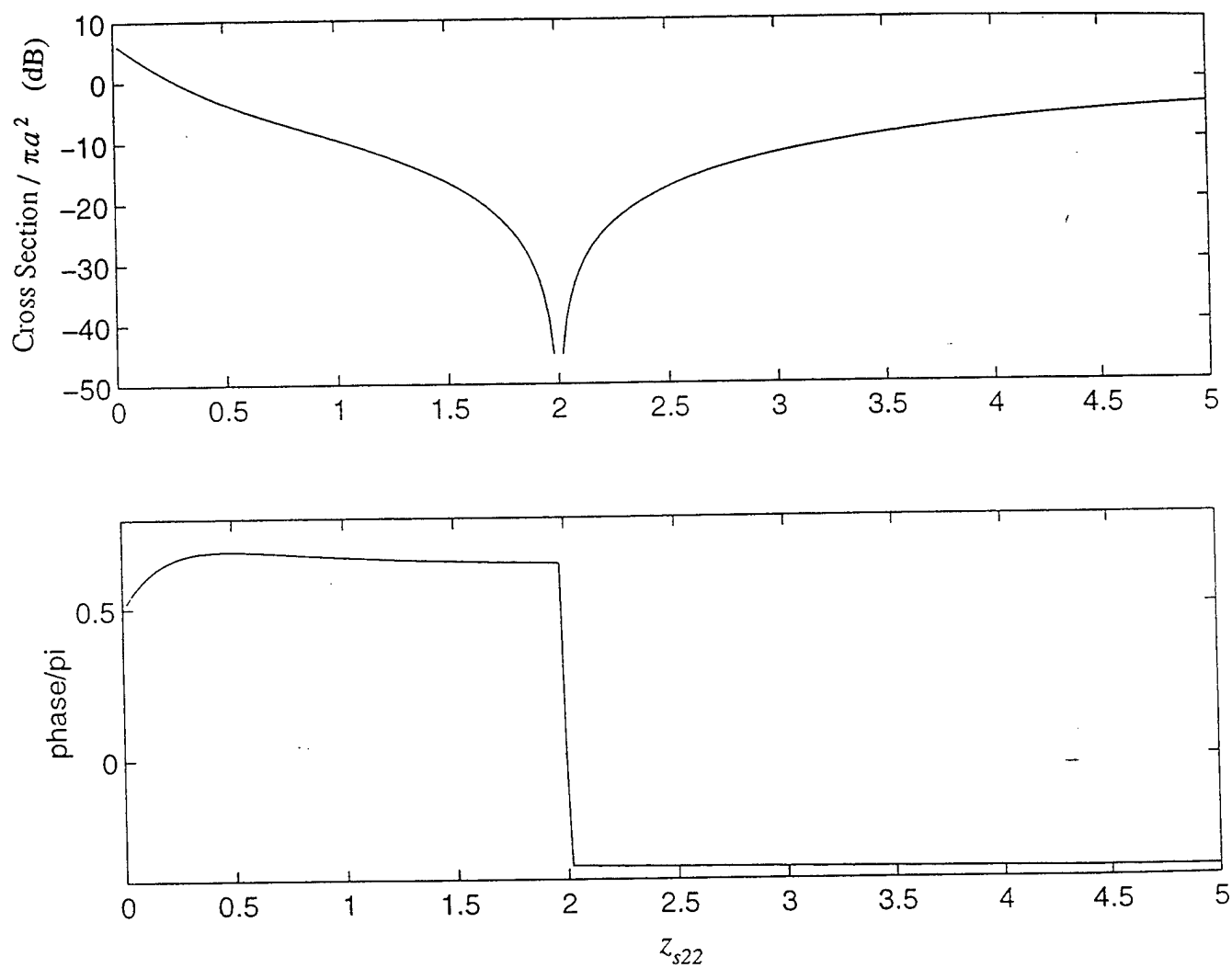


Figure 5-3.

$$Z^+ = 0, \quad Z^- = Z_s = \begin{bmatrix} 0.5 & 0 \\ 0 & z_{s22} \end{bmatrix}$$

Axial backscattering ( $h/a = 6$ ,  $2h/\lambda = 3.194$ )

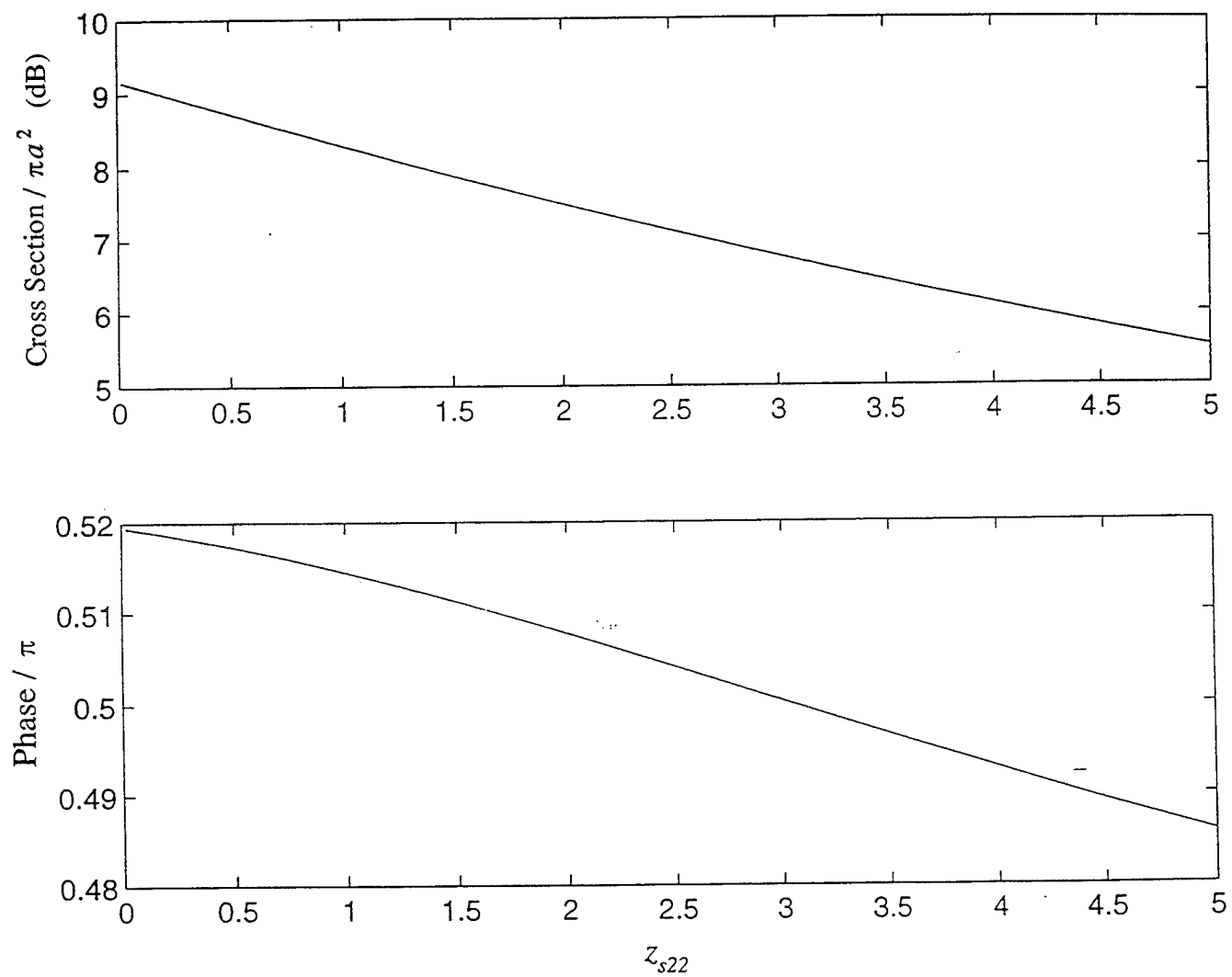


Figure 5-4.



$$Z^- = 0, \quad Z^+ = Z_s = \begin{bmatrix} 0.5 & 0 \\ 0 & z_{s22} \end{bmatrix}$$

Axial backscattering ( $h/a = 6, 2h/\lambda = 3.194$ )

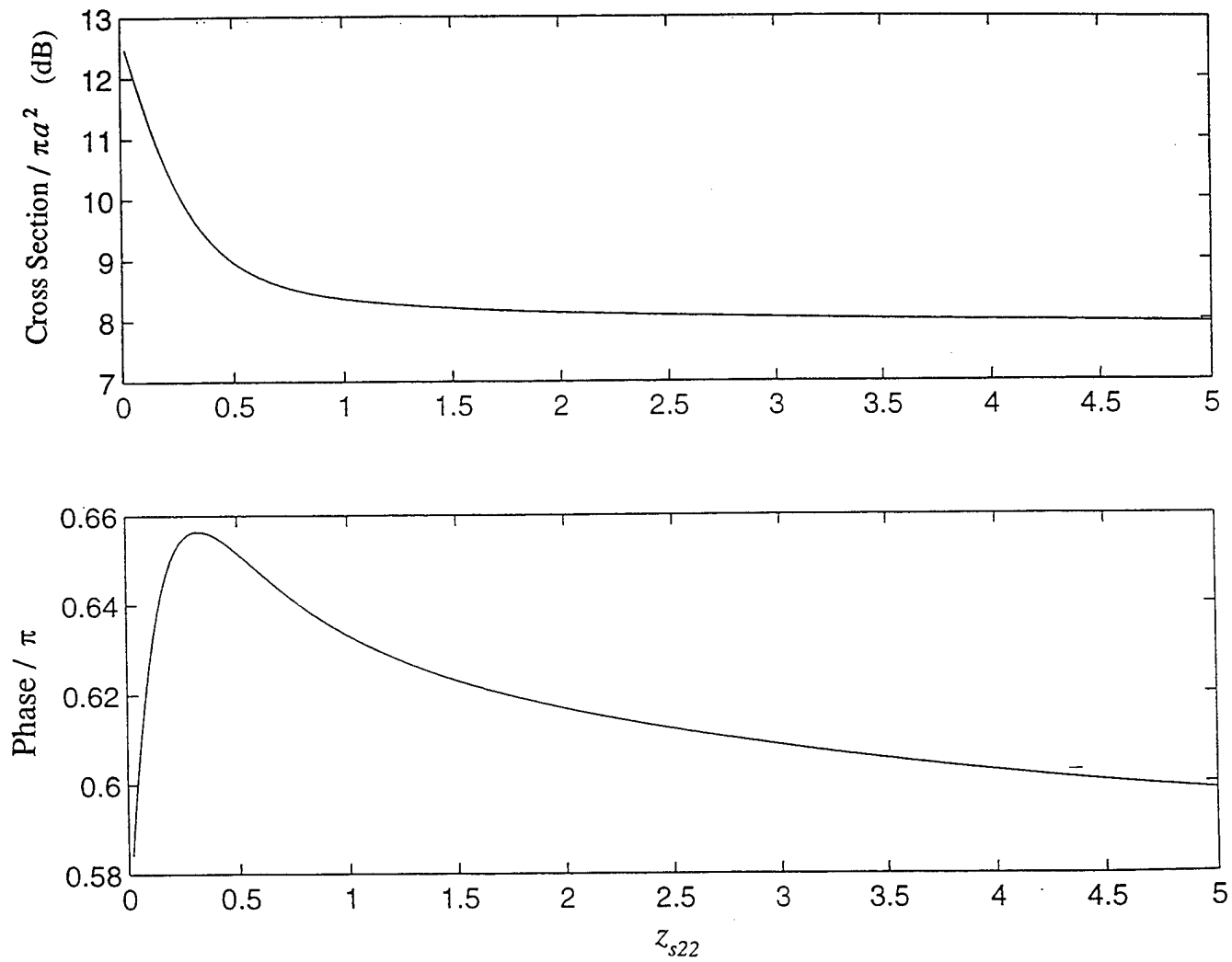


Figure 5-5.

$$Z^+ = Z^- = Z_s = \begin{bmatrix} 0.5 & 0 \\ 0 & z_{22} \end{bmatrix}$$

Axial backscattering ( $h/a = 6$ ,  $2h/\lambda = 4.865$ )

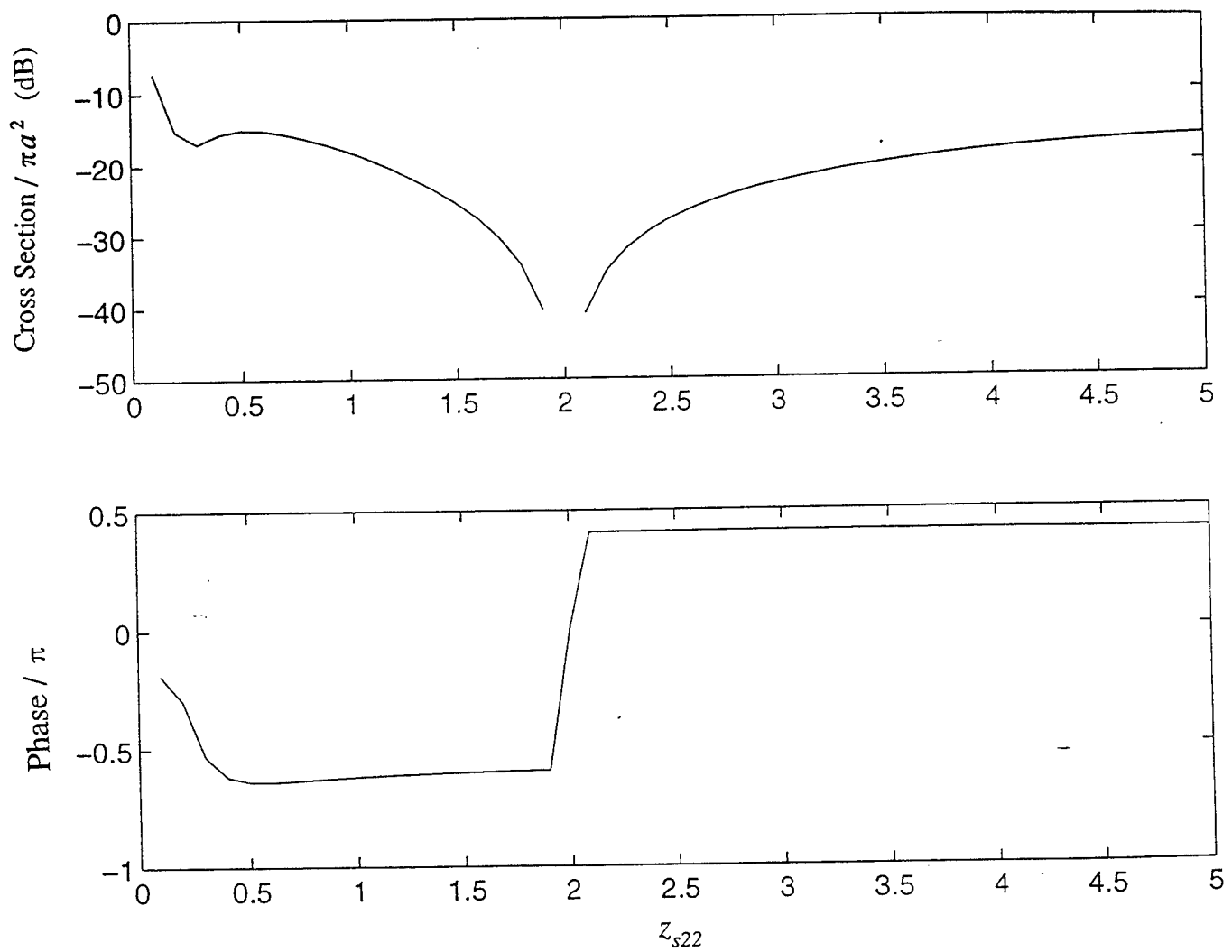


Figure 5-6.

$$Z^+ = 0, \quad Z^- = Z_s = \begin{bmatrix} 0.5 & 0 \\ 0 & z_{s22} \end{bmatrix}$$

Axial backscattering ( $h/a = 6$ ,  $2h/\lambda = 4.865$ )

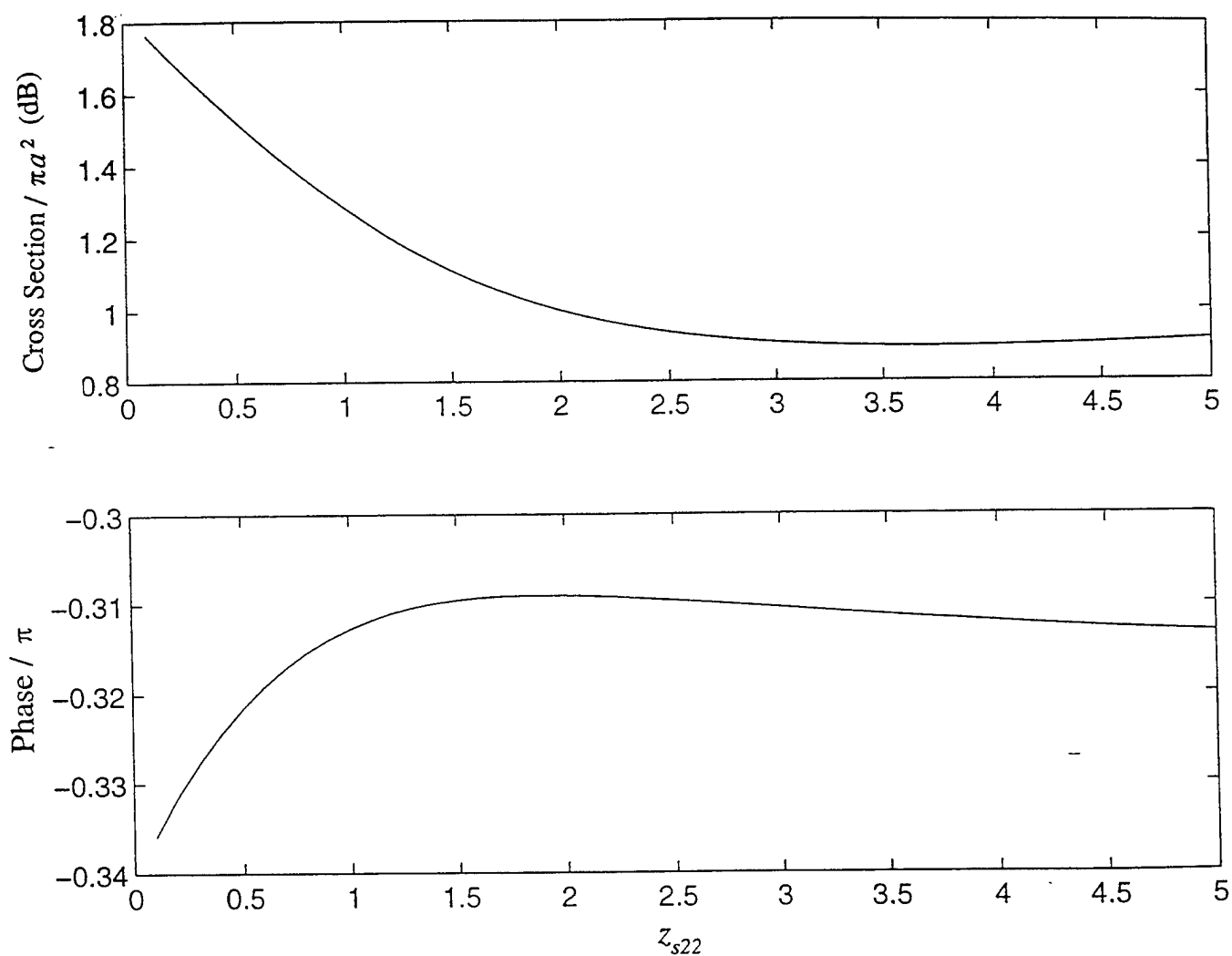


Figure 5-7.

$$Z^- = 0, \quad Z^+ = Z_s = \begin{bmatrix} 0.5 & 0 \\ 0 & z_{s22} \end{bmatrix}$$

Axial backscattering ( $h/a = 6$ ,  $2h/\lambda = 4.865$ )

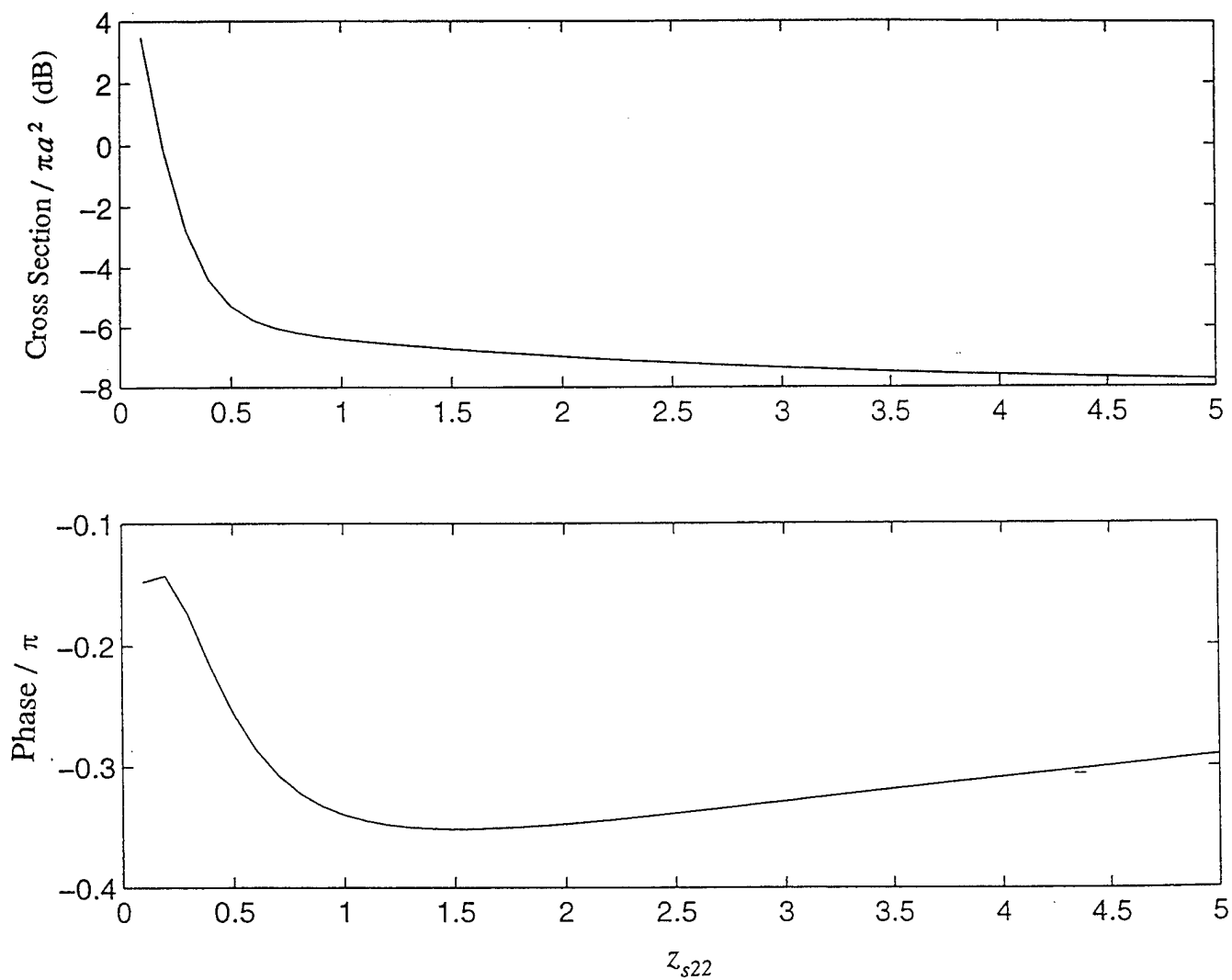


Figure 5-8.

$$Z^+ = 0, \quad Z^- = Z_s = \begin{bmatrix} 0.5 & 0 \\ 0 & 2.0 \end{bmatrix}$$

Axial backscattering ( $h/a = 6$ )

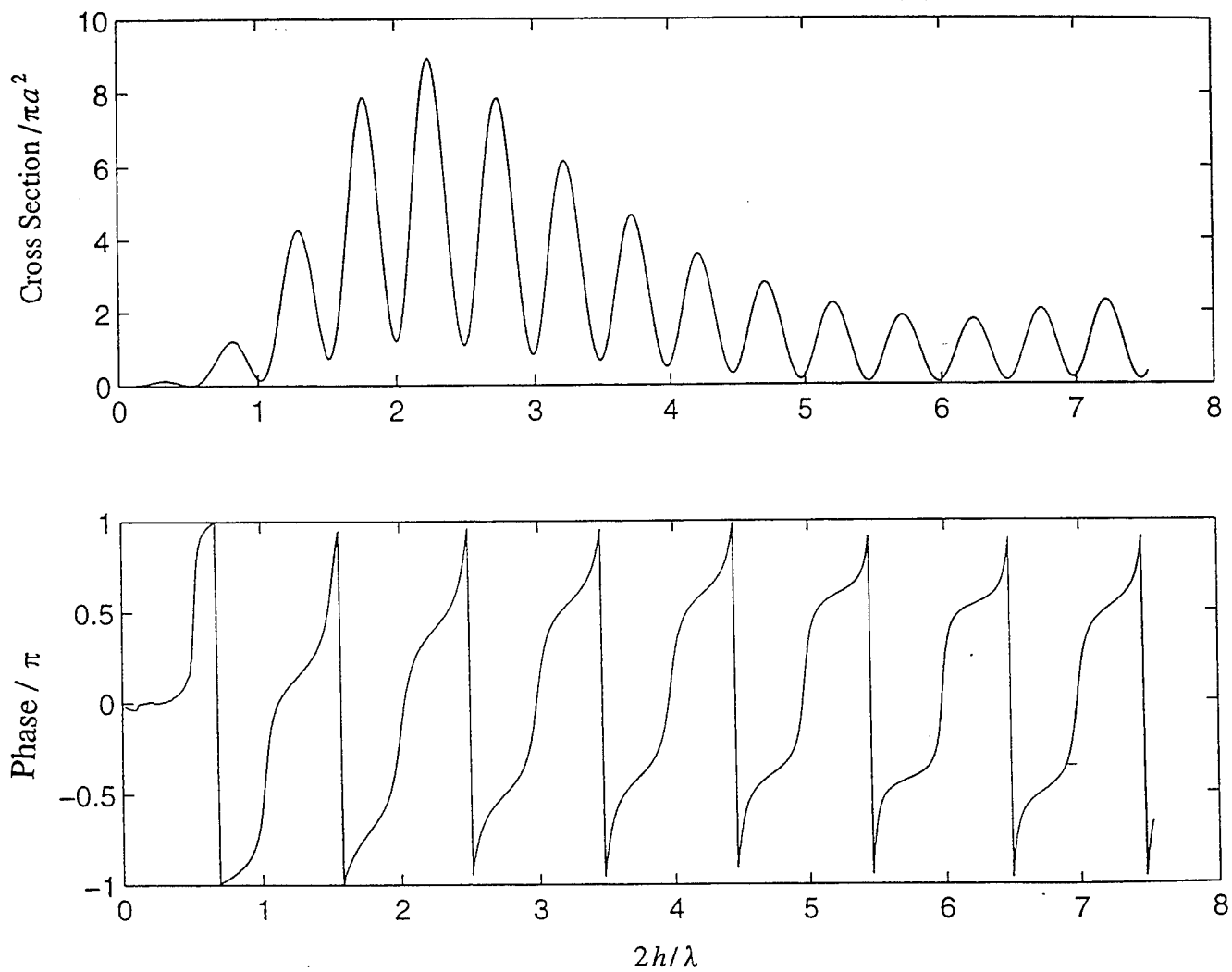


Figure 5-9.

$$Z^- = 0, \quad Z^+ = Z_s = \begin{bmatrix} 0.5 & 0 \\ 0 & 2.0 \end{bmatrix}$$

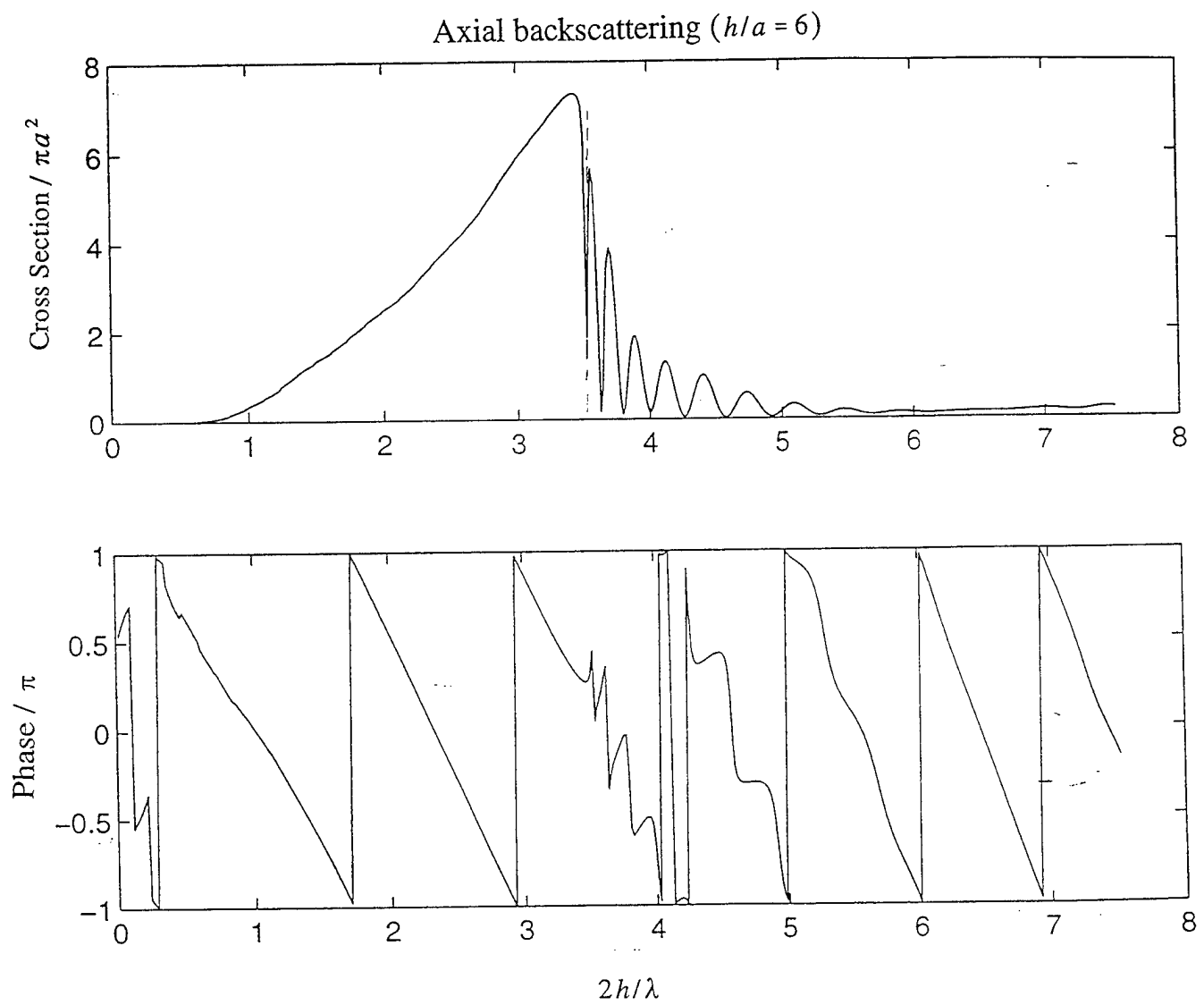


Figure 5-10.

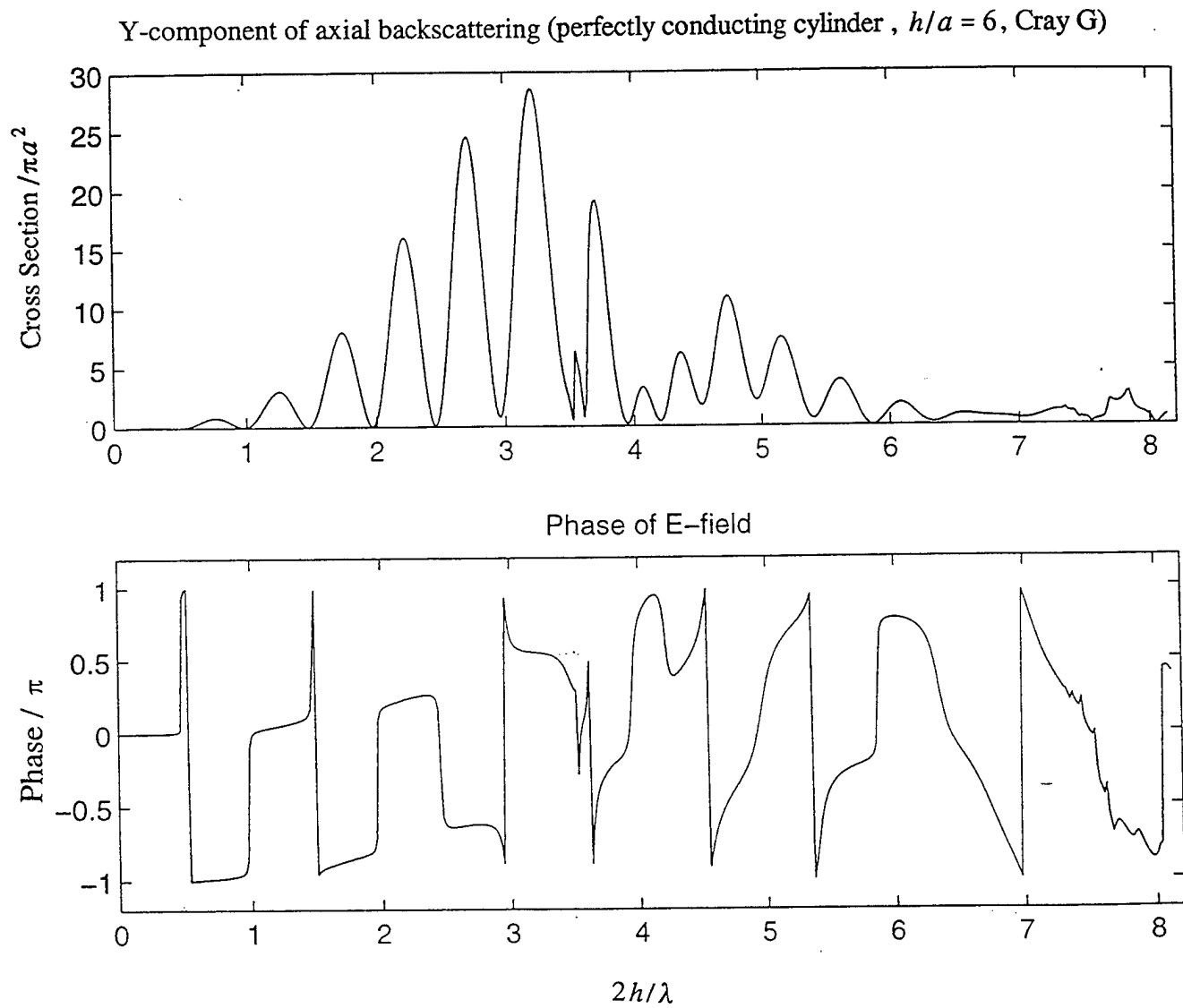


Figure 5-11

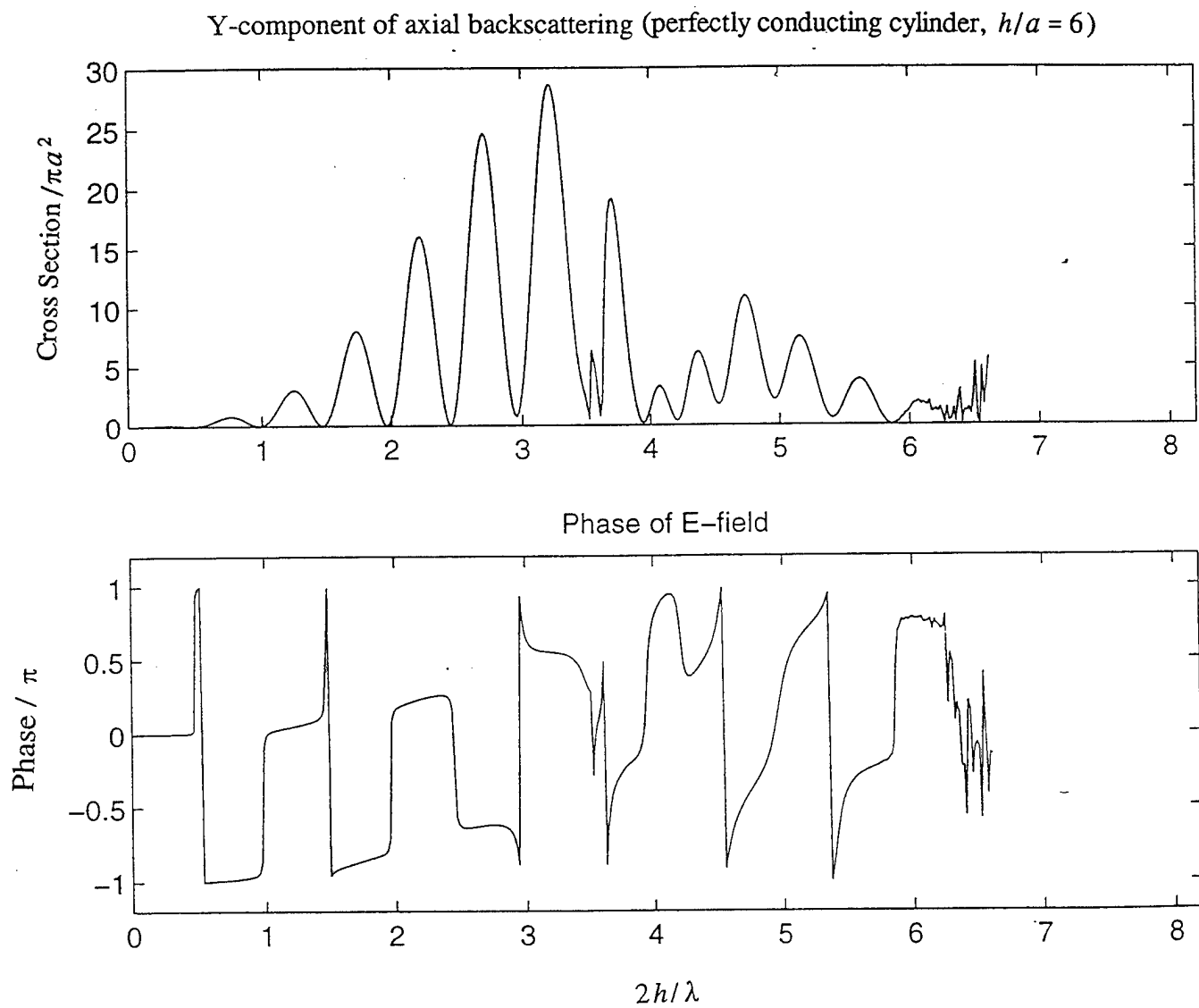


Figure 5-12.



$$Z^+ = \begin{bmatrix} 0.5 & 0.3 \\ 0.3 & 0.4 \end{bmatrix} \quad Z^- = \begin{bmatrix} 0.4 & 0.3 \\ 0.3 & 0.5 \end{bmatrix}$$

Y-component of axial backscattering ( $h/a = 6$ , Cray G)

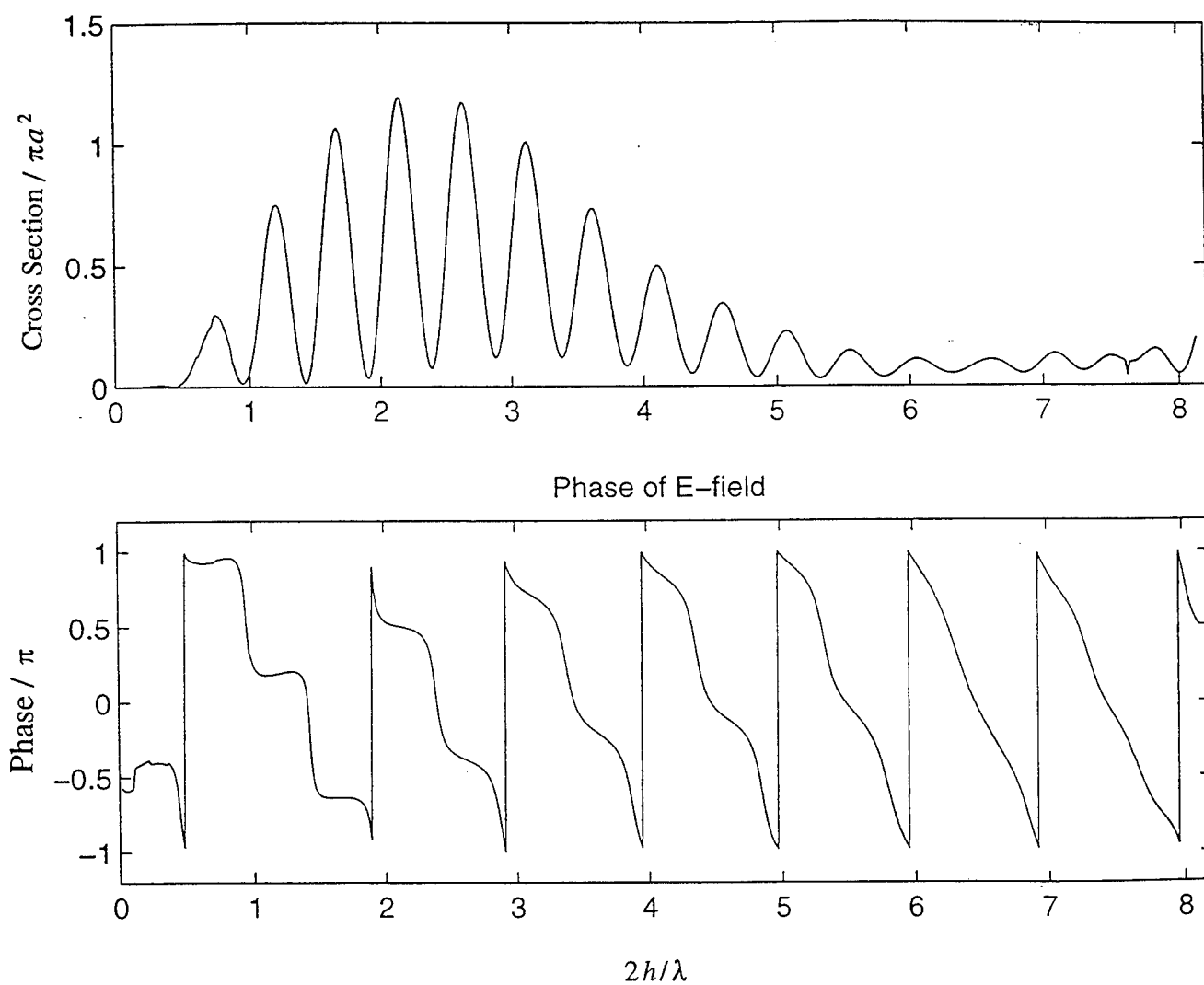


Figure 5-13.

$$Z^+ = \begin{bmatrix} 0.5 & 0.3 \\ 0.3 & 0.4 \end{bmatrix} \quad Z^- = \begin{bmatrix} 0.4 & 0.3 \\ 0.3 & 0.5 \end{bmatrix}$$

Y-component of axial backscattering ( $h/a = 6$ )

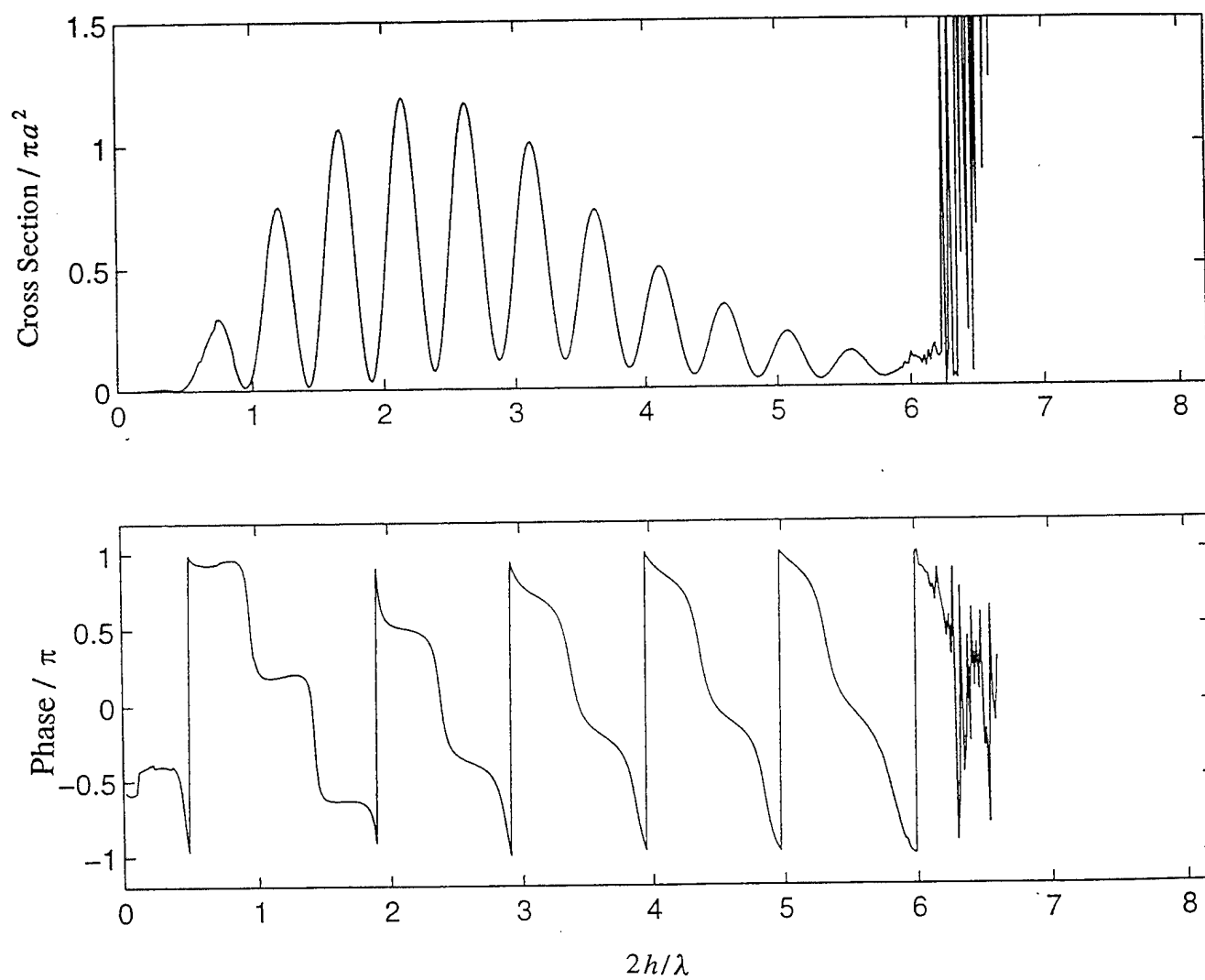


Figure 5-14.

$$Z^+ = \begin{bmatrix} 0.5 & 0.3 \\ 0.3 & 0.4 \end{bmatrix} \quad Z^- = \begin{bmatrix} 0.4 & 0.3 \\ 0.3 & 0.5 \end{bmatrix}$$

X-component of axial backscattering ( $h/a = 6$ , Cray G)

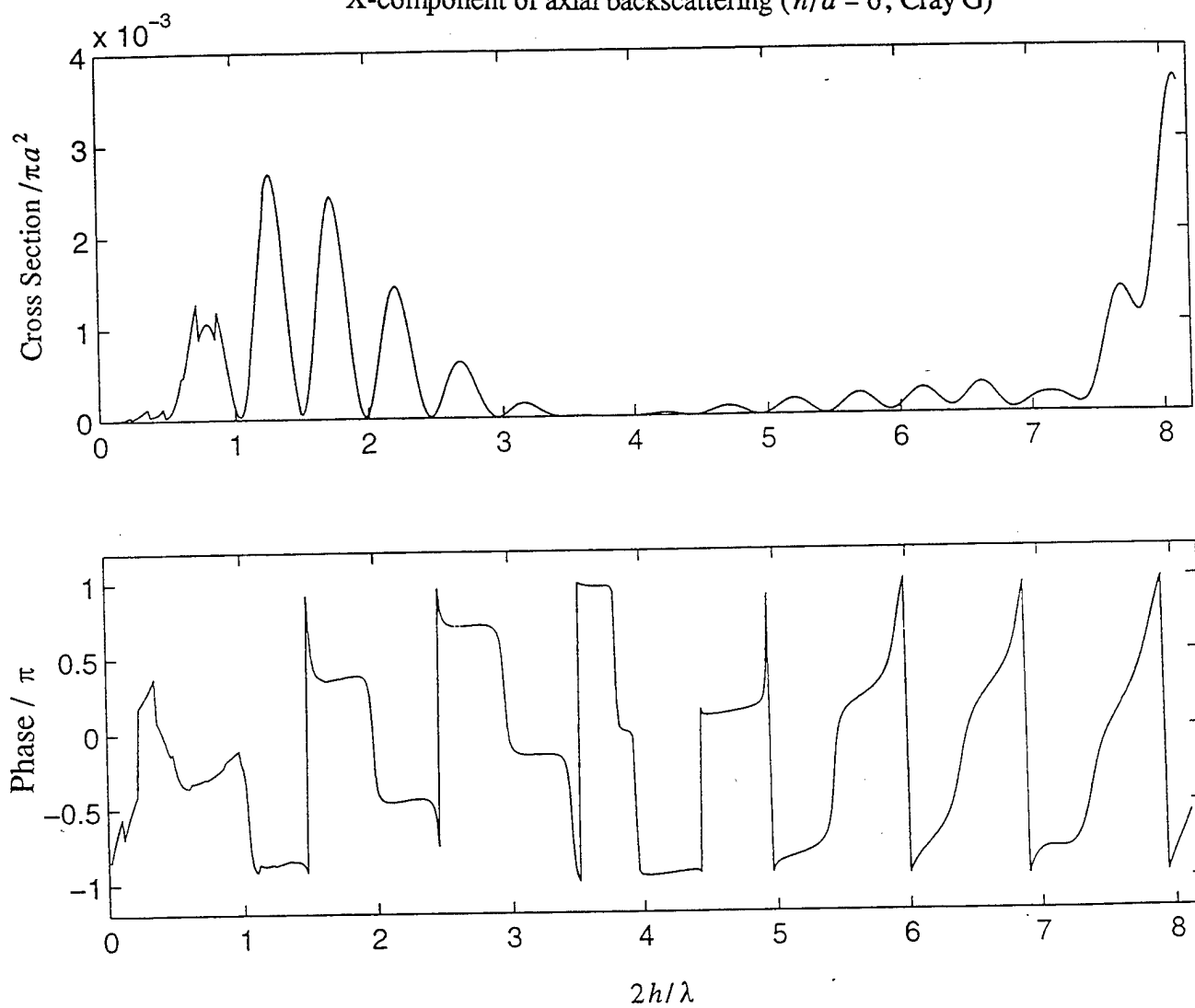


Figure 5-15.

$$Z^+ = \begin{bmatrix} 0.5 & 0.3 \\ 0.3 & 0.4 \end{bmatrix} \quad Z^- = \begin{bmatrix} 0.4 & 0.3 \\ 0.3 & 0.5 \end{bmatrix}$$

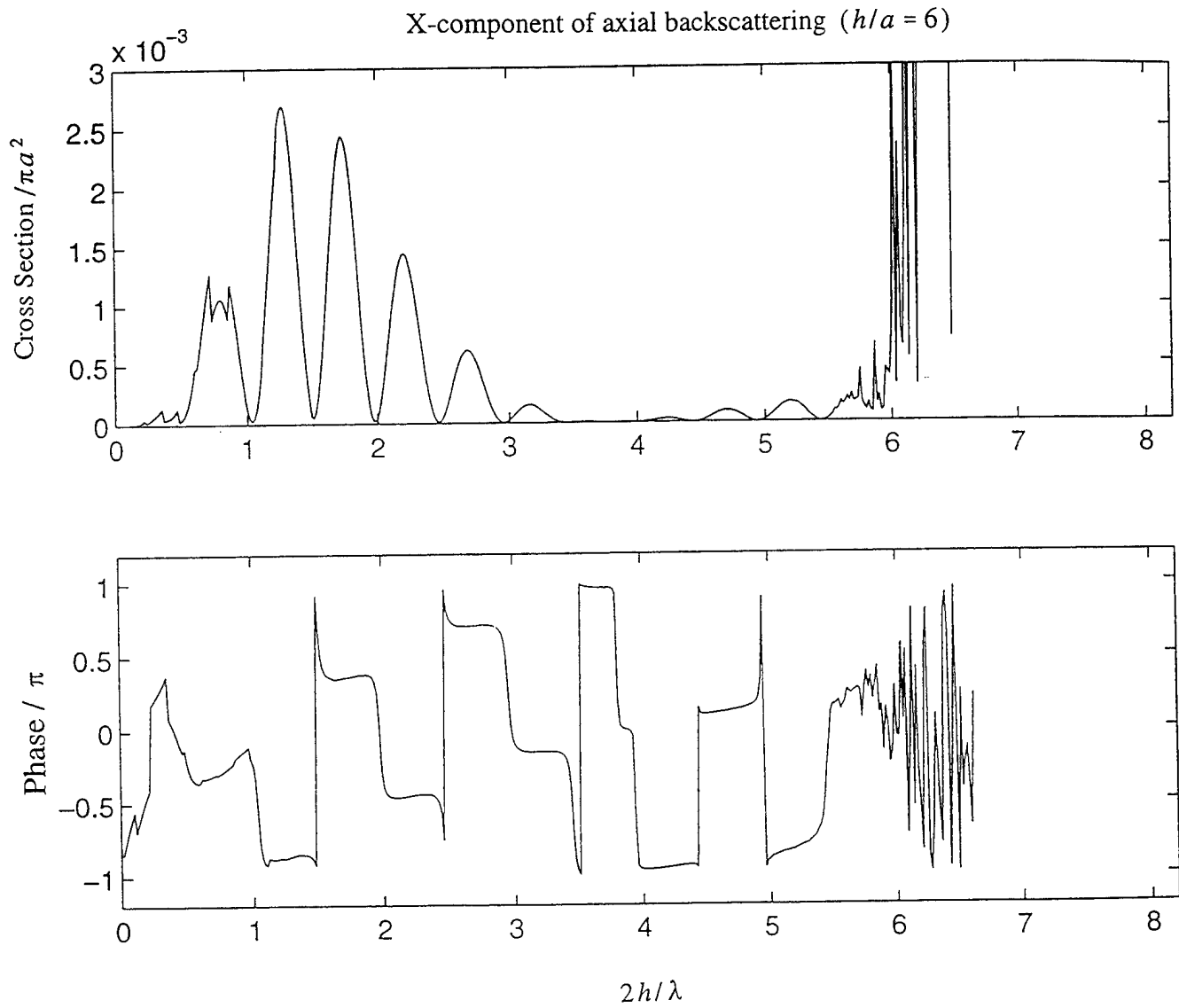


Figure 5-16.

## VI. CONCLUSIONS

In this thesis, the sum-difference surface current formulation is introduced for solving electromagnetic boundary value problems when impedances are specified on both sides of a surface. For an impedance coated body, the body can be treated as being a surface separating the space into two regions of identical medium. For an exterior problem, the impedance normalized to the medium on the inside surface,  $Z^-$ , can be chosen arbitrarily; and for an interior problem, that on the outside surface,  $Z^+$ , can be arbitrary. The choice when  $Z^- = -Z^+$  is of particular interest because the integrodifferential equation has only the sum of the equivalent electric surface currents on the outside and the inside surfaces as its unknown to be solved.

This formulation preserves the duality nature of Maxwell's equations and carries it over into the algebraic form of the integrodifferential operators in the equations for the sum currents. Since a  $90^\circ$  rotation is equivalent to undergoing a duality transform for an incident plane wave, this particular symmetry in the algebraic form of the operators leads to the sufficient conditions that if  $Z^+ = Z^- = \pm \sigma_2$ , or if  $Z^+$  and  $Z^-$  are symmetric and  $\det Z^+ = \det Z^- = 1$ , the on-axis backscattering of an anisotropic impedance coated scatterer having a  $90^\circ$  rotational symmetry will be eliminated. Note that in the symmetric case,  $Z^+$  and  $Z^-$  may vary with location. This is an extension of Weston's result [4] for which the surface impedance is isotropic.

A FORTRAN program has been written which accepts the geometry of the cylinder, the surface impedance matrices, the incident wave frequency, direction and its polarization in terms of TE, TM or some linear combination of the two. It computes the sum surface currents and the far field radiation in the directions specified, including the strength and the phase of each field component. It also breaks down the sum surface currents into the outside and the inside currents.

The results of computation using this program agree with measured data of

backscattering from conducting tubular cylinders over a frequency band of more than three octaves. For a cylinder coated with surface impedance matrices satisfying the criteria for null on-axis backscattering, the numerical computation also validated the theoretical assertion.

Difficulties have been encountered about the computational accuracy in the evaluation of the double series Chebyshev expansion coefficients of the Green's function  $G_n^{p,q}(l_1, l_2)$  and its  $l_2$ -derivative by double power series sum when the length of the cylinder is large compared to the wavelength: a compiler with a 64-bit double precision number can only handle a cylinder having a length up to about 6.2 wavelengths. Further work to explore the feasibility of asymptotic evaluation of these coefficients is recommended.

## APPENDIX PROGRAM LISTING

### A. INCLUDE FILES

#### REALTP.INC

```

C   TYPE STATEMENTS FOR REAL AND INTEGERS AND DEFINITIONS OF CONSTANTS.
      IMPLICIT DOUBLE PRECISION (A, B, D-H, O-Z)
      IMPLICIT INTEGER*4 (I-N)
      PARAMETER (PI=3.14159265358979323846264338327D0,PI2=PI+PI,
+       PISQ=PI*PI)
      PARAMETER (ONE=1.D0,TWO=2.D0,THR=3.D0,HXD=16.D0,ZERO=0.D0,
+       DEGPI=180.D0,EPS8=2.220446049250313D-16)
      PARAMETER (ONEN=-ONE,HALF=ONE/TWO,THIR=ONE/THR,QUAR=HALF*HALF)

```

#### CMXPXT.INC

```

C   IMPLICIT TYPE STATEMENT AND CONSTANTS FOR COMPLEX NUMBERS.
      IMPLICIT DOUBLE COMPLEX (C)
      PARAMETER (CZERO=(0.D0,0.D0),CONE=(1.D0,0.D0))
      PARAMETER (CONEN=(-1.D0,0.D0),CI1=(0.D0,1.D0),CI2=(0.D0,-1.D0))

```

### B. INPUT DATA FILES

#### CLYGEOM.PRM

```

30      Maximum kh (integer)
5       Maximum ka (integer)
8       NREGNS (integer)

```

#### CYLFLPT.PRM

```

1024    floating point zero I0BIT (1024 bits)
64      floating point precision IFPBIT (64 bits)

```

#### INPUTDAT.PRM

```

.1D-1    DKA0, minimum ka (REAL) in the computation
.875D-2  DINCA, increment of ka (REAL)
40       NSTR, start point (INTEGER) in the computation
479      NEND, end point (INTEGER) in the computation
6.D0     RHA, ratio of h and a- (REAL)
1        IE, if incident wave is TE-polarized it is 1, otherwise 0
0        IM, if incident wave is TM-polarized it is 1, otherwise 0
0.D0     THETA1, incident angle (REAL) is limited to 0 to 90 degree
6        NTHTAO, total number (INTEGER) of angle of THATA
3        NPHI, total number (INTEGER) of angle of PHI0 to be computed
0.D0     THETA0, initial theta angle (REAL)
1.D0     DELTHO, increment of theta angle (REAL)
0.D0     PHIA, initial theta angle (REAL)
12.D0    DELPHI, increment of phi angle (REAL)
0        IK, set 1 to compute scattering currents on outer and inner surface

```

#### IMPEDNCE.PRM

```

0        IZ, if perfect conducting, IZ=0; otherwise, IZ=1.
(.5D0,0.D0) Impedance Z+ (phi phi)
(.4D0,0.D0) Impedance Z- (phi phi)
(.3D0,0.D0) Impedance Z+ (phi z)
(.3D0,0.D0) Impedance Z- (phi z)
(.3D0,0.D0) Impedance Z+ (z phi)

```

```

      (.3D0,0.D0)      Impedance Z- (z phi)
      (.4D0,0.D0)      Impedance Z+ (z z)
      (.5D0,0.D0)      Impedance Z- (z z)

```

~~~~~

## C. SETUP PROGRAM AND CREATED FILES

```

      PROGRAM SETUP
C*****
C NOTES:The format statement 1001 need to be revised if other than
C        double precision real numbers are used for DKHMAX and DKAMAX.
C        Statement 1001 needs to be revised if KHMAX or KAMAX exceeds
C        3 digits.
C        The format statement 1002 need to be revised if other than
C        double precision real numbers are used for FZERO AND PRECSN.
C        Statement 1002 needs to be revised if IOBIT exceeds 6 digits
C        or IFPBIT exceeds 4 digits.
C*****
C
      INCLUDE 'REALTP.INC'
      INCLUDE 'CMPXTP.INC'
      OPEN (20,FILE='CYLGEOM.PRM',IOSTAT=IOS,STATUS='OLD')
      IF(IOS.NE. 0) THEN
      WRITE(*,9000)
9000  FORMAT ('Cannot find the file CYLGEOM.PRM containing the ',/,
+ ' maximum values for ka and kh, and the parameter NREGNS.')
      STOP
      END IF
      READ (20,*) KHMAX
      READ (20,*) KAMAX
      READ (20,*) NREGNS
      CLOSE (20)
      OPEN (20,FILE='CYLFLPT.PRM',IOSTAT=IOS,STATUS='OLD')
      IF(IOS.NE. 0) THEN
      WRITE(*,9001)
9001  FORMAT ('Cannot find the file CYLFLPT.PRM containing floating',/,
+ ' point zero bit IOBIT and precision IFPBIT.')
      STOP
      END IF
      READ(20,*) IOBIT
      READ(20,*) IFPBIT
      CLOSE (20)
      OPEN (21,FILE='LIMITS.INC',STATUS='UNKNOWN')
      WRITE (21,1001) KHMAX, KAMAX
      WRITE (21,1002) IOBIT, IFPBIT, IFPBIT
      CLOSE (21)
1001  FORMAT (6X,'PARAMETER (DKHMAX= ',I3,'.D0, DKAMAX= ',I3,'.D0)')
1002  FORMAT (6X,'PARAMETER (FZERO=',I6,'.D0, PRECSN=',I4,'.D0,',
+ ' IFPBIT=',I4,'.D0)')
C
C Part 2
      DKHMAX=KHMAX
      DKAMAX=KAMAX
      ONEDEL=ONE-EPS8
      KQDIM=INT((DKHMAX/PI)*NREGNS+ONEDEL)
      KNDIM=INT((DKAMAX/TWO)*NREGNS+ONEDEL)
      KQDIM=MAX(KQDIM,1)
      KNDIM=MAX(KNDIM,1)
      OPEN (21,FILE='MAINDM.INC',STATUS='UNKNOWN')
      WRITE (21,1003) NREGNS, KNDIM, KQDIM
      WRITE (21,1004)
      WRITE (21,1005)
      WRIE (21,1006)
      CLOSE (21)
1003  FORMAT (6X,'PARAMETER (NREGNS=',I2,', KNDIM=',I3,
+ ', KQDIM=',I3,')')

```



```

1004 FORMAT (6X,'PARAMETER (KNDIM1=KNDIM+1, KQDIM1=KQDIM+1)')
1005 FORMAT (6X,'PARAMETER (KXCRT=2*KQDIM1, KCRNT=4*KQDIM1)')
1006 FORMAT (6X,'PARAMETER (MAXNG=KNDIM1, MAXPEG=KQDIM/2+1,',
+      ' MAXPOG=KQDIM1/2)')
C
C Part 3
      FZERO=IOBIT
      REFC=FZERO*LOG(TWO)-LOG(PI2)-ONE
      REFH=HALF*(REFC-LOG(DKHMAX))
      REFA=HALF*(REFC-LOG(DKAMAX))
C
      KQ2=KQDIM+2
      DMXM=KQ2
      DO 100 WHILE ((DMXM+HALF)*(LOG(DMXM/DKHMAX)+ONEN) .LT. REFH)
      DMXM=DMXM+ONE
100    CONTINUE
      MXMREG=INT(DMXM)
C
      MXMSNG=INT(TWO*DKHMAX+ONEDEL)
      MXMSNG=MAX(IFPBIT,MXMSNG,KQ2)+KNDIM+1
      OPEN (21,FILE='GPQNDM.INC',STATUS='UNKNOWN')
      WRITE (21,1009) MXMREG, MXMSNG
      CLOSE (21)
1009 FORMAT (6X,'PARAMETER (MXMREG=',I4,', MXMSNG=',I4,')')
      STOP
      END

```

#### GPQNDM.INC

```

      PARAMETER (DKHMAX= 30.D0, DKAMAX= 5.D0)
      PARAMETER (FZERO= 1024.D0, PRECSN= 64.D0, IFPBIT= 64)

```

#### LIMITS.INC

```

      PARAMETER (DKHMAX= 30.D0, DKAMAX= 5.D0)
      PARAMETER (FZERO= 1024.D0, PRECSN= 64.D0, IFPBIT= 64)

```

#### MAINDM.INC

```

      PARAMETER (NREGNS= 8, KNDIM= 20, KQDIM= 77)
      PARAMETER (KNDIM1=KNDIM+1, KQDIM1=KQDIM+1)
      PARAMETER (KXCRT=2*KQDIM1, KCRNT=4*KQDIM1)
      PARAMETER (MAXNG=KNDIM1, MAXPEG=KQDIM/2+1, MAXPOG=KQDIM1/2)

```

## D. PROGRAM MAIN

```

PROGRAM MAIN
*****
      INCLUDE 'REALTP.INC'
      INCLUDE 'CMPXTP.INC'
      COMMON /GCONST/ DKH,DKA,HH,HA,HSQ,DASQ,HSQN,DASQN,HHSQ,HDASQ,
+      RAH,RAHSQ,DHA,DAH
      COMMON /INPUT1/ DKA0,DINCA,NSTR,NEND,RHA
      COMMON /INPUT2/ IE,IM,THETAI,THESINI,THECOSI,RTHEI
      COMMON /INPUT4/ IZ,IK,IS,NYSM
C
      CALL CHKINPUT
      OPEN (21,FILE='rhzz41.dz',STATUS='UNKNOWN')
      DO 8001 IS=NSTR,NEND
      DS=IS
      DKA=DKA0+DINCA*DS
      DKH=DKA*RHA
      CALL MAXODM
      CALL RAPQMT
      CALL GNPQFN
      CALL BCKSCFL(IR,CESTH,CESPH)

```

```

      CALL RCSPAREA(CESTH,CESPH)
8001  CONTINUE
      CLOSE(21)
      STOP
      END

```

## E. SUBROUTINE CHKINPUT

```

SUBROUTINE CHKINPUT
C*****
  INCLUDE 'REALTP.INC'
  INCLUDE 'LIMITS.INC'
  COMMON /INPUT1/ DKA0,DINCA,NSTR,NEND,RHA
  COMMON /INPUT2/ IE,IM,THETAI,THESINI,THECOSI,RTHEI
  COMMON /INPUT3/ RTHE,RDELT,RPHI,RDELP,NTHTAO,NPHI,THESIN,THECOS,
+
  + RHPI
  COMMON /INPUT4/ IZ,IK,IS,NYSM
C*****
  OPEN(20,FILE='INPUTDAT.PRM',IOSTAT=IOS,STATUS='OLD')
  IF(IOS.NE.0) THEN
    WRITE(*,*) 'Fail to open input file INPUTDAT.PRM'
    STOP
  END IF
C*****
C Input kh and ka. These values are passed to other
C parts of this program through the common block /INPUT1/.
  READ(20,*) DKA0
  READ(20,*) DINCA
  READ(20,*) NSTR
  READ(20,*) NEND
  READ(20,*) RHA
C*****
C Check against maximum kh and ka values.
  NBTW=NEND-NSTR
  DKH0=DKA0*RHA
  DKA1=DINCA*NBTW+DKA0
  DKH1=DKA1*RHA
  IF (DKH1.GT. DKHMAX) THEN
    IF (DKA1.GT. DKAMAX) THEN
      WRITE(*,*) 'Both kh and ka values exceed the maximum allowed.'
    ELSE
      WRITE(*,*) 'The input kh value exceeds the maximum value allowed.'
    END IF
    WRITE(*,*) 'The execution is terminated.'
    CLOSE(20)
    STOP
  ELSE IF (DKA1.GT. DKAMAX) THEN
    WRITE(*,*) 'The input ka value exceeds the maximum value allowed.'
    WRITE(*,*) 'The execution is terminated.'
    CLOSE(20)
    STOP
  END IF
  IF ((DINCH.LT. ZERO).OR. (DINCA.LT. ZERO)) THEN
    WRITE(*,*) 'The increment DINCH or DINCA is less than zero.'
    WRITE(*,*) 'The execution is terminated.'
    CLOSE(20)
    STOP
  END IF
C*****
C Input the incident angle (THETAI) and polarization (TE or TM) of the
C incident wave. The incident angle is limited to 0 to 90
C degrees. SIN(THETAI) and COS(THETAI) are computed also. These
C parameters are passed to other parts of this program through the
C common block /INPUT2/.
  READ(20,*) IE
  READ(20,*) IM
  READ(20,*) THETAI

```

```

C Check the input value of incident wave
  IF ((IE .NE. 1) .AND. (IE .NE. 0)) THEN
    WRITE (*,*) 'Improperly specified the polarization of incident ',
+ 'wave. program is stopped.'
    STOP
  ELSE IF ((IM .NE. 1) .AND. (IM .NE. 0)) THEN
    WRITE (*,*) 'Improperly specified the polarization of incident ',
+ 'wave. program is stopped.'
    CLOSE(20)
    STOP
  END IF

  IF ((THETAI .LT. ZERO) .OR. (THETAI .GT. 90.)) THEN
    WRITE (*,*) 'Improperly specified incident angle. ',
+ 'program is stopped.'
    CLOSE(20)
    STOP
  END IF

C Calculate SIN(THETAI) and COS(THETAI)
  RTHEI=THETAI*PI/DEGPI
  THESINI=SIN(RTHEI)
  THECOSI=COS(RTHEI)
C*****
C Input the angles theta and phi at which the scattered fields are
C to be computed. They are specified in terms of the initial theta
C (THETA0) and phi (PHI0) angles, their respective increments DELTHO
C and DELPHI, and the total numbers of angles NTHTAO and NPHI to be
C computed. Thus NTHTAO and NPHI must be integers greater than 1. If
C either NTHTAO=0 or NPHI=0, no bistatically scattered fields will be
C computed. Note that the scattered electric field components are
C computed for all the phi-angles at a fixed theta, before the
C theta-angle is varied. All angles are specified in degrees. Theta is
C limited to 0 to 180 while phi is limited to 0 to 360 degrees.
C SIN(THETA0) and COS(THETA0) are computed also. These parameters are
C passed to other parts of this program through the common block /INPUT3/.
  READ(20,*) NTHTAO
  READ(20,*) NPHI
  IF ((NTHTAO .LT. 0) .OR. (NPHI .LT. 0)) THEN
    WRITE(*,*) 'Improperly specified number of output angles. ',
+ 'Program is stopped.'
    STOP
  ELSE IF ((NTHTAO .EQ. 0) .OR. (NPHI .EQ. 0)) THEN
    CLOSE(20)
    WRITE(*,*) 'Desired bistatic scattered field direction has not ',
+ 'been (properly) specified, they will not be computed.'
    NTHTAO=0
    NPHI=0
    THETA0=ZERO
    DELTHO=ZERO
    PHI0=ZERO
    DELPHI=ZERO
  ELSE
    READ(20,*) THETA0
    READ(20,*) DELTHO
    READ(20,*) PHIA
    READ(20,*) DELPHI
  END IF
  READ(20,*) IK
C*****
C Check input values.
  IF ((DKH0 .LE. ZERO) .OR. (DKH1 .LE. ZERO)) THEN
    WRITE(*,*) 'Invalid kh, program is stopped.'
    STOP
  END IF
  IF ((DKA0 .LE. ZERO) .OR. (DKA1 .LE. ZERO)) THEN
    WRITE(*,*) 'Invalid ka, program is stopped.'
    STOP
  END IF

```

```

        IF ((DKA0 .GT. DKH0) .OR. (DKA1 .GT. DKH1)) THEN
        WRITE(*,*) 'ka/kh > 1, program is stopped.'
        STOP
        END IF
C Output angle checking not required:
        IF (NTHTAO .EQ. 0) GO TO 200
C Chcking output angles:
        IF ((THETA0 .LT. ZERO) .OR. (THETA0 .GT. DEGPI)) THEN
        WRITE(*,*) 'The first output theta-angle lies outside the 0 to ',
+ '180 degrees range. Program is stopped.'
        STOP
        END IF
        THTAIF=THETA0+(NTHTAO-1)*DELTHO
        IF ((THTAIF .LT. ZERO) .OR. (THTAIF .GT. DEGPI)) THEN
        WRITE(*,*) 'Some of the specified output theta-angles lie',
+ 'outside the 0 to 180 degrees range. Program is stopped.'
        STOP
        END IF
        PHIMX=TWO*DEGPI
        IF ((PHIO .LT. ZERO) .OR. (PHIO .GT. PHIMX)) THEN
        WRITE(*,*) 'The first output phi-angle lies outside the 0 to ',
+ '360 degrees range. Program is stopped.'
        STOP
        END IF
        PHIF=PHIO+(NPHI-1)*DELPHI
        IF ((PHIF .LT. ZERO) .OR. (PHIF .GT. TWO*DEGPI)) THEN
        WRITE(*,*) 'Some of the output phi-angles lie outside',
+ 'the 0 to 360 degrees range. Program is stopped.'
        STOP
        END IF
200 CONTINUE
        DPI=PI/DEGPI
        RTHE=THETA0*DPI
        RPHI=PHIO*DPI
        RDELT=DELTHO*DPI
        RDELP=DELPHI*DPI
        RHPI=90.*DPI
        THESIN=SIN(RTHE)
        THECOS=COS(RTHE)
        RETURN
        END

```

## F. SUBROUTINE MAXODM

```

SUBROUTINE MAXODM
C *****
  INCLUDE 'REALTP.INC'
  INCLUDE 'MAINDM.INC'
  COMMON /CRNTDM/ NMAX,MXNG,IQMAX,IQMAX1,IQMAX2,IXCRNT,ICRNT,MXQEG,
+     MXQOG
  COMMON /GCONST/ DKH,DKA,HH,HA,HSQ,DASQ,HSQN,DASQN,HHSQ,HDASQ,
+     RAH,RAHSQ,DHA,DAH
  COMMON /RTHETA/ DL1COSI,DL2SINI,DL1
  COMMON /INPUT1/ DKA0,DINCA,NSTR,NEND,RHA
  COMMON /INPUT2/ IE,IM,THETA1,THESINI,THECOSI,RTHEI
  COMMON /INPUT3/ RTHE,RDELT,RPHI,RDELP,NTHTAO,NPHI,THESIN,THECOS,
+     RHPI
C
  ONEDEL=ONE-EPS8
  IQMAX=INT((DKH/PI)*NREGNS+ONEDEL)
  IQMAX=MAX(IQMAX,1)
  IQMAX1=IQMAX+1
  IQMAX2=IQMAX1+2
  IXCRNT=2*IQMAX1
  ICRNT=4*IQMAX1
  MXQEG=IQMAX/2+1
  MXQOG=IQMAX1/2

```

```

C      NMAX=INT((DKA/TWO)*NREGNS+ONEDEL)
      NMAX=MAX(NMAX,1)
      MXNG=NMAX+1
C
C      Evaluate SIN and COS functions to pass along /
      DL1COSI=DKH*THECOSI
      DL2SINI=DKA*THESINI
      DLL=DKH*DL2SINI
C
C      Evaluate geometrical values to pass along /GCONST/.
      HH=HALF*DKH
      HA=HALF*DKA
      HSQ=DKH*DKH
      DASQ=DKA*DKA
      HSQN=-HSQ
      DASQN=-DASQ
      HHSQ=QUAR*HSQ
      HDASQ=QUAR*DASQ
      RAH=DKA/DKH
      RAHSQ=RAH*RAH
      DHA=DKH*HA
      DAH=HH*HA
C
      RETURN
      END

```

## G. SUBROUTINE RAPQMT

```

SUBROUTINE RAPQMT
C*****
      INCLUDE 'REALTP.INC'
      INCLUDE 'CMPXTP.INC'
      INCLUDE 'MAINDM.INC'
      DIMENSION CO(2,2), CIR(2,2)
      DIMENSION CZSUM(2,2), CZDIF(2,2), CR1(4,4), CR2(4,4), CR3(4,4)
      DIMENSION CRPQ1(KCRNT,KCRNT), CRPQ2(KCRNT,KCRNT),
+      CRPQ31(KCRNT,KCRNT), CRPQ32(KCRNT,KCRNT)
      COMMON /INPUT2/ IE,IM,THETAI,THESINI,THECOSI,RTHEI
      COMMON /INPUT4/ IZ,IK,IS,NYSM
      COMMON /XPQTMP1/ CRPQ1,CRPQ2
      COMMON /XPQTMP2/ CRPQ31,CRPQ32
      COMMON /CRNTDM/ NMAX,MXNG,IQMAX,IQMAX1,IQMAX2,IXCRNT,ICRNT,MXQEG,
+      MXQOG
C
      OPEN (20,FILE='IMPEDNCE.PRM',IOSTAT=IOS,STATUS='OLD')
      IF (IOS.NE. 0) THEN
        WRITE(*,9000)
9000  FORMAT ('Cannot find the file IMPEDNCE1.PRM containing the ',/,
+  'impedances of the inner and outer surfaces.')
        STOP
      END IF
C
      READ(20,*) IZ
      IF ((IZ.NE. 0).AND. (IZ.NE. 1)) THEN
        WRITE (*,*) 'Improperly specified the impedance of cylinder ',
+  'surface. program is stopped.'
        CLOSE(20)
        STOP
      END IF
      IF (IZ.EQ. 0) THEN
        CLOSE(20)
        RETURN
      END IF
C Set up the matrix when Z and Delta are diagonal, or not diagonal but  $n \leq 0$ .
C Initialize the matrix CRPQ1
      DO 200 I=1,KCRNT

```

```

        DO 100 J=1,KCRNT
        CRPQ1(I,J)=CZERO
        CRPQ2(I,J)=CZERO
        CRPQ31(I,J)=CZERO
        CRPQ32(I,J)=CZERO
100      CONTINUE
200      CONTINUE
        DO 400 I=1,2
        DO 300 J=1,2
        READ (20,*) CO(I,J)
        READ (20,*) CIR(I,J)
        CZSUM(I,J)=(CO(I,J)+CIR(I,J))*HALF
        CZDIF(I,J)=(CO(I,J)-CIR(I,J))*HALF
300      CONTINUE
400      CONTINUE
        CLOSE (20)
        CZ11=CZSUM(1,1)
        CZ12=CZSUM(1,2)
        CZ21=CZSUM(2,1)
        CZ22=CZSUM(2,2)
        CRDET=CZ11*CZ22-CZ12*CZ21
        CD11=CZDIF(1,1)
        CD12=CZDIF(1,2)
        CD21=CZDIF(2,1)
        CD22=CZDIF(2,2)
        IF (CRDET.EQ. CZERO) THEN
        WRITE (*,9001)
        STOP
        END IF
C Check the diagonalization of the impedance matrixes
        NSYM=1
        IF (CZ12 .NE. CZERO) THEN
        NSYM=0
        ELSE IF (CZ21 .NE. CZERO) THEN
        NSYM=0
        ELSE IF (CD12 .NE. CZERO) THEN
        NSYM=0
        ELSE IF (CD21 .NE. CZERO) THEN
        NSYM=0
        END IF
        CRDTZ=CONE/CRDET
        CR1(1,1)=CZ11-(CD11*CD11*CZ22-CD11*CD12*CZ21-CD11*CD21*CZ12
+         +CD12*CD21*CZ11)*CRDTZ
        CR1(1,2)=CZ12-(CD11*CD12*CZ22-CD12*CD12*CZ21-CD11*CD22*CZ12
+         +CD12*CD22*CZ11)*CRDTZ
        CR1(2,1)=CZ21-(CD11*CD21*CZ22-CD11*CD22*CZ21-CD21*CD21*CZ12
+         +CD21*CD22*CZ11)*CRDTZ
        CR1(2,2)=CZ22-(CD12*CD21*CZ22-CD12*CD22*CZ21-CD21*CD22*CZ12
+         +CD22*CD22*CZ11)*CRDTZ
        CR1(1,3)=(CD12*CZ11-CD11*CZ12)*CRDTZ
        CR1(1,4)=(CD12*CZ21-CD11*CZ22)*CRDTZ
        CR1(2,3)=(CD22*CZ11-CD21*CZ12)*CRDTZ
        CR1(2,4)=(CD22*CZ21-CD21*CZ22)*CRDTZ
        CR1(3,1)=(CD11*CZ21-CD21*CZ11)*CRDTZ
        CR1(3,2)=(CD12*CZ21-CD22*CZ11)*CRDTZ
        CR1(4,1)=(CD11*CZ22-CD21*CZ12)*CRDTZ
        CR1(4,2)=(CD12*CZ22-CD22*CZ12)*CRDTZ
        CR1(3,3)=CZ11*CRDTZ
        CR1(3,4)=CZ21*CRDTZ
        CR1(4,3)=CZ12*CRDTZ
        CR1(4,4)=CZ22*CRDTZ
C
        DO 1300 IQE=0,MXQEG
        IQE1=IQE+1
        IQ=2*IQE
        DQ=IQ
        DQ1=IQ+1
        IQX1=4*IQ+1

```

```

IQX2=IQX1+1
IQX3=IQX2+1
IQX4=IQX3+1
DO 1100 IPE=0,MXQEG
IPE1=IPE+1
IP=2*IPE
IPX1=4*IP+1
IPX2=IPX1+1
IPX3=IPX2+1
IPX4=IPX3+1
DP=IP
DP1=IP+1
DBPHI=PISQ*(DP+DQ1)*(DP1-DQ)
BPHI=4.D0/DBPHI
DBZ=PISQ*(DP+DQ1)*(DP1-DQ)*(DP1+DQ1+ONE)*(DP-DQ1)
BZ=-8.D0*DQ1/DBZ
CRPQ1(IPX1,IQX1)=CR1(1,1)*BPHI
CRPQ1(IPX2,IQX1)=CR1(2,1)*BPHI
CRPQ1(IPX3,IQX1)=CR1(3,1)*BPHI
CRPQ1(IPX4,IQX1)=CR1(4,1)*BPHI
CRPQ1(IPX1,IQX2)=CR1(1,2)*BZ
CRPQ1(IPX2,IQX2)=CR1(2,2)*BZ
CRPQ1(IPX3,IQX2)=CR1(3,2)*BZ
CRPQ1(IPX4,IQX2)=CR1(4,2)*BZ
CRPQ1(IPX1,IQX3)=CR1(1,3)*BPHI
CRPQ1(IPX2,IQX3)=CR1(2,3)*BPHI
CRPQ1(IPX3,IQX3)=CR1(3,3)*BPHI
CRPQ1(IPX4,IQX3)=CR1(4,3)*BPHI
CRPQ1(IPX1,IQX4)=CR1(1,4)*BZ
CRPQ1(IPX2,IQX4)=CR1(2,4)*BZ
CRPQ1(IPX3,IQX4)=CR1(3,4)*BZ
CRPQ1(IPX4,IQX4)=CR1(4,4)*BZ
1100 CONTINUE
1300 CONTINUE
DO 2300 IQO=0,MXQOG
IQO1=IQO+1
IQ=2*IQO+1
IQX1=4*IQ+1
IQX2=IQX1+1
IQX3=IQX2+1
IQX4=IQX3+1
DQ=IQ
DQ1=IQ+1
DO 2200 IPO=0,MXQOG
IPO1=IPO+1
IP=2*IPO+1
IPX1=4*IP+1
IPX2=IPX1+1
IPX3=IPX2+1
IPX4=IPX3+1
DP=IP
DP1=IP+1
DBPHI=PISQ*(DP+DQ1)*(DP1-DQ)
BPHI=4.D0/DBPHI
DBZ=PISQ*(DP+DQ1)*(DP1-DQ)*(DP1+DQ1+ONE)*(DP-DQ1)
BZ=-8.D0*DQ1/DBZ
CRPQ1(IPX1,IQX1)=CR1(1,1)*BPHI
CRPQ1(IPX2,IQX1)=CR1(2,1)*BPHI
CRPQ1(IPX3,IQX1)=CR1(3,1)*BPHI
CRPQ1(IPX4,IQX1)=CR1(4,1)*BPHI
CRPQ1(IPX1,IQX2)=CR1(1,2)*BZ
CRPQ1(IPX2,IQX2)=CR1(2,2)*BZ
CRPQ1(IPX3,IQX2)=CR1(3,2)*BZ
CRPQ1(IPX4,IQX2)=CR1(4,2)*BZ
CRPQ1(IPX1,IQX3)=CR1(1,3)*BPHI
CRPQ1(IPX2,IQX3)=CR1(2,3)*BPHI
CRPQ1(IPX3,IQX3)=CR1(3,3)*BPHI
CRPQ1(IPX4,IQX3)=CR1(4,3)*BPHI

```

```

CRPQ1(IPX1,IQX4)=CR1(1,4)*BZ
CRPQ1(IPX2,IQX4)=CR1(2,4)*BZ
CRPQ1(IPX3,IQX4)=CR1(3,4)*BZ
CRPQ1(IPX4,IQX4)=CR1(4,4)*BZ
2200 CONTINUE
2300 CONTINUE
C Set up the matrix Rpq utilized when Z or Delta is nor diagonal, and n < 0.
CR2(1,2)=-CR1(1,2)
CR2(2,1)=-CR1(2,1)
CR2(1,3)=-CR1(1,3)
CR2(2,4)=-CR1(2,4)
CR2(3,1)=-CR1(3,1)
CR2(4,2)=-CR1(4,2)
CR2(3,4)=-CR1(3,4)
CR2(4,3)=-CR1(4,3)
CR2(1,1)=CR1(1,1)
CR2(2,2)=CR1(2,2)
CR2(1,4)=CR1(1,4)
CR2(2,3)=CR1(2,3)
CR2(3,2)=CR1(3,2)
CR2(4,1)=CR1(4,1)
CR2(3,3)=CR1(3,3)
CR2(4,4)=CR1(4,4)
DO 3300 IQE=0,MXQEG
IQE1=IQE+1
IQ=2*IQE
DQ=IQ
DQ1=IQ+1
IQX1=4*IQ+1
IQX2=IQX1+1
IQX3=IQX2+1
IQX4=IQX3+1
DO 3100 IPE=0,MXQEG
IPE1=IPE+1
IP=2*IPE
IPX1=4*IP+1
IPX2=IPX1+1
IPX3=IPX2+1
IPX4=IPX3+1
DP=IP
DP1=IP+1
DBPHI=PISQ*(DP+DQ1)*(DP1-DQ)
BPHI=4.D0/DBPHI
DBZ=PISQ*(DP+DQ1)*(DP1-DQ)*(DP1+DQ1+ONE)*(DP-DQ1)
BZ=-8.D0*DQ1/DBZ
CRPQ2(IPX1,IQX1)=CR2(1,1)*BPBI
CRPQ2(IPX2,IQX1)=CR2(2,1)*BPBI
CRPQ2(IPX3,IQX1)=CR2(3,1)*BPBI
CRPQ2(IPX4,IQX1)=CR2(4,1)*BPBI
CRPQ2(IPX1,IQX2)=CR2(1,2)*BZ
CRPQ2(IPX2,IQX2)=CR2(2,2)*BZ
CRPQ2(IPX3,IQX2)=CR2(3,2)*BZ
CRPQ2(IPX4,IQX2)=CR2(4,2)*BZ
CRPQ2(IPX1,IQX3)=CR2(1,3)*BPBI
CRPQ2(IPX2,IQX3)=CR2(2,3)*BPBI
CRPQ2(IPX3,IQX3)=CR2(3,3)*BPBI
CRPQ2(IPX4,IQX3)=CR2(4,3)*BPBI
CRPQ2(IPX1,IQX4)=CR2(1,4)*BZ
CRPQ2(IPX2,IQX4)=CR2(2,4)*BZ
CRPQ2(IPX3,IQX4)=CR2(3,4)*BZ
CRPQ2(IPX4,IQX4)=CR2(4,4)*BZ
3100 CONTINUE
3300 CONTINUE
DO 4300 IQO=0,MXQOG
IQO1=IQO+1
IQ=2*IQO+1
IQX1=4*IQ+1
IQX2=IQX1+1

```



```

IQX3=IQX2+1
IQX4=IQX3+1
DQ=IQ
DQ1=IQ+1
DO 4200 IPO=0,MXQOG
IPO1=IPO+1
IP=2*IPO+1
IPX1=4*IP+1
IPX2=IPX1+1
IPX3=IPX2+1
IPX4=IPX3+1
DP=IP
DP1=IP+1
DBPHI=PISQ*(DP+DQ1)*(DP1-DQ)
BPHI=4/DBPHI
DBZ=PISQ*(DP+DQ1)*(DP1-DQ)*(DP1+DQ1+ONE)*(DP-DQ1)
BZ=-8.*DQ1/DBZ
CRPQ2(IPX1,IQX1)=CR2(1,1)*BPHI
CRPQ2(IPX2,IQX1)=CR2(2,1)*BPHI
CRPQ2(IPX3,IQX1)=CR2(3,1)*BPHI
CRPQ2(IPX4,IQX1)=CR2(4,1)*BPHI
CRPQ2(IPX1,IQX2)=CR2(1,2)*BZ
CRPQ2(IPX2,IQX2)=CR2(2,2)*BZ
CRPQ2(IPX3,IQX2)=CR2(3,2)*BZ
CRPQ2(IPX4,IQX2)=CR2(4,2)*BZ
CRPQ2(IPX1,IQX3)=CR2(1,3)*BPHI
CRPQ2(IPX2,IQX3)=CR2(2,3)*BPHI
CRPQ2(IPX3,IQX3)=CR2(3,3)*BPHI
CRPQ2(IPX4,IQX3)=CR2(4,3)*BPHI
CRPQ2(IPX1,IQX4)=CR2(1,4)*BZ
CRPQ2(IPX2,IQX4)=CR2(2,4)*BZ
CRPQ2(IPX3,IQX4)=CR2(3,4)*BZ
CRPQ2(IPX4,IQX4)=CR2(4,4)*BZ
4200 CONTINUE
4300 CONTINUE
C Prepare a matrix for computing the scattering currents on the outer
C and the inner surfaces
IF (IK.NE.1) THEN
RETURN
END IF
CR3(1,1)=-CR1(4,1)
CR3(1,2)=-CR1(4,2)
CR3(1,3)=-CR1(4,3)
CR3(1,4)=-CR1(4,4)
CR3(3,1)=CR1(2,1)
CR3(3,2)=CR1(2,2)
CR3(3,3)=CR1(2,3)
CR3(3,4)=CR1(2,4)
CR3(2,1)=CR1(3,1)
CR3(2,2)=CR1(3,2)
CR3(2,3)=CR1(3,3)
CR3(2,4)=CR1(3,4)
CR3(4,1)=-CR1(1,1)
CR3(4,2)=-CR1(1,2)
CR3(4,3)=-CR1(1,3)
CR3(4,4)=-CR1(1,4)
C
DO 5200 IQE=0,MXQEG
IQE1=IQE+1
IQ=2*IQE
DQ=IQ
DQ1=IQ+1
IQX1=4*IQ+1
IQX2=IQX1+1
IQX3=IQX2+1
IQX4=IQX3+1
DO 5100 IPE=0,MXQEG
IPE1=IPE+1

```

```

IP=2*IPE
IPX1=4*IP+1
IPX2=IPX1+1
IPX3=IPX2+1
IPX4=IPX3+1
DP=IP
DP1=IP+1
DBPHI=PISQ*(DP+DQ1)*(DP1-DQ)
BPHI=4./DBPHI
DBZ=PISQ*(DP+DQ1)*(DP1-DQ)*(DP1+DQ1+ONE)*(DP-DQ1)
BZ=-8.*DQ1/DBZ
CRPQ31(IPX1,IQX1)=(CONE+CR3(1,1))*BPHI
CRPQ31(IPX2,IQX1)=CR3(2,1)*BPHI
CRPQ31(IPX3,IQX1)=CR3(3,1)*BPHI
CRPQ31(IPX4,IQX1)=CR3(4,1)*BPHI
CRPQ31(IPX1,IQX2)=CR3(1,2)*BZ
CRPQ31(IPX2,IQX2)=(CONE+CR3(2,2))*BZ
CRPQ31(IPX3,IQX2)=CR3(3,2)*BZ
CRPQ31(IPX4,IQX2)=CR3(4,2)*BZ
CRPQ31(IPX1,IQX3)=CR3(1,3)*BPHI
CRPQ31(IPX2,IQX3)=CR3(2,3)*BPHI
CRPQ31(IPX3,IQX3)=(CONE+CR3(3,3))*BPHI
CRPQ31(IPX4,IQX3)=CR3(4,3)*BPHI
CRPQ31(IPX1,IQX4)=CR3(1,4)*BZ
CRPQ31(IPX2,IQX4)=CR3(2,4)*BZ
CRPQ31(IPX3,IQX4)=CR3(3,4)*BZ
CRPQ31(IPX4,IQX4)=(CONE+CR3(4,4))*BZ
C
CRPQ32(IPX1,IQX1)=(CONE-CR3(1,1))*BPHI
CRPQ32(IPX2,IQX1)=-CR3(2,1)*BPHI
CRPQ32(IPX3,IQX1)=-CR3(3,1)*BPHI
CRPQ32(IPX4,IQX1)=-CR3(4,1)*BPHI
CRPQ32(IPX1,IQX2)=-CR3(1,2)*BZ
CRPQ32(IPX2,IQX2)=(CONE-CR3(2,2))*BZ
CRPQ32(IPX3,IQX2)=-CR3(3,2)*BZ
CRPQ32(IPX4,IQX2)=-CR3(4,2)*BZ
CRPQ32(IPX1,IQX3)=-CR3(1,3)*BPHI
CRPQ32(IPX2,IQX3)=-CR3(2,3)*BPHI
CRPQ32(IPX3,IQX3)=(CONE-CR3(3,3))*BPHI
CRPQ32(IPX4,IQX3)=-CR3(4,3)*BPHI
CRPQ32(IPX1,IQX4)=-CR3(1,4)*BZ
CRPQ32(IPX2,IQX4)=-CR3(2,4)*BZ
CRPQ32(IPX3,IQX4)=-CR3(3,4)*BZ
CRPQ32(IPX4,IQX4)=(CONE-CR3(4,4))*BZ
5100 CONTINUE
5200 CONTINUE
C
DO 6200 IQO=0,MXQOG
IQO1=IQO+1
IQ=2*IQO+1
DQ=IQ
DQ1=IQ+1
IQX1=4*IQ+1
IQX2=IQX1+1
IQX3=IQX2+1
IQX4=IQX3+1
DO 6100 IPO=0,MXQOG
IPE1=IPO+1
IP=2*IPO+1
IPX1=4*IP+1
IPX2=IPX1+1
IPX3=IPX2+1
IPX4=IPX3+1
DP=IP
DP1=IP+1
DBPHI=PISQ*(DP+DQ1)*(DP1-DQ)
BPHI=4./DBPHI
DBZ=PISQ*(DP+DQ1)*(DP1-DQ)*(DP1+DQ1+ONE)*(DP-DQ1)

```

```

BZ=-8.*DQ1/DBZ
CRPQ31(IPX1,IQX1)=(CONE+CR3(1,1))*BPHI
CRPQ31(IPX2,IQX1)=CR3(2,1)*BPHI
CRPQ31(IPX3,IQX1)=CR3(3,1)*BPHI
CRPQ31(IPX4,IQX1)=CR3(4,1)*BPHI
CRPQ31(IPX1,IQX2)=CR3(1,2)*BZ
CRPQ31(IPX2,IQX2)=(CONE+CR3(2,2))*BZ
CRPQ31(IPX3,IQX2)=CR3(3,2)*BZ
CRPQ31(IPX4,IQX2)=CR3(4,2)*BZ
CRPQ31(IPX1,IQX3)=CR3(1,3)*BPHI
CRPQ31(IPX2,IQX3)=CR3(2,3)*BPHI
CRPQ31(IPX3,IQX3)=(CONE+CR3(3,3))*BPHI
CRPQ31(IPX4,IQX3)=CR3(4,3)*BPHI
CRPQ31(IPX1,IQX4)=CR3(1,4)*BZ
CRPQ31(IPX2,IQX4)=CR3(2,4)*BZ
CRPQ31(IPX3,IQX4)=CR3(3,4)*BZ
CRPQ31(IPX4,IQX4)=(CONE+CR3(4,4))*BZ
C
CRPQ32(IPX1,IQX1)=(CONE-CR3(1,1))*BPHI
CRPQ32(IPX2,IQX1)=-CR3(2,1)*BPHI
CRPQ32(IPX3,IQX1)=-CR3(3,1)*BPHI
CRPQ32(IPX4,IQX1)=-CR3(4,1)*BPHI
CRPQ32(IPX1,IQX2)=-CR3(1,2)*BZ
CRPQ32(IPX2,IQX2)=(CONE-CR3(2,2))*BZ
CRPQ32(IPX3,IQX2)=-CR3(3,2)*BZ
CRPQ32(IPX4,IQX2)=-CR3(4,2)*BZ
CRPQ32(IPX1,IQX3)=-CR3(1,3)*BPHI
CRPQ32(IPX2,IQX3)=-CR3(2,3)*BPHI
CRPQ32(IPX3,IQX3)=(CONE-CR3(3,3))*BPHI
CRPQ32(IPX4,IQX3)=-CR3(4,3)*BPHI
CRPQ32(IPX1,IQX4)=-CR3(1,4)*BZ
CRPQ32(IPX2,IQX4)=-CR3(2,4)*BZ
CRPQ32(IPX3,IQX4)=-CR3(3,4)*BZ
CRPQ32(IPX4,IQX4)=(CONE-CR3(4,4))*BZ
6100    CONTINUE
6200    CONTINUE
        RETURN
9001    FORMAT('The given inside and outside impedance have a singular',
+          ' sum. Execution is terminated.')
        END

```

## H. SUBROUTINE GNPQFN

```

SUBROUTINE GNPQFN
C*****
INCLUDE 'REALTP.INC'
INCLUDE 'MAINDM.INC'
COMMON /GCONST/ DKH,DKA,HH,HA,HSQ,DASQ,HSQN,DASQN,HHSQ,HDASQ,
+      RAH,RAHSQ,DHA,DAH
CHARACTER FILEEVEN1*12, FILEODD1*12
C Set up the file names
NC1=INT(DKA)
DC=NC1
NC=100000.*DKH+NC1
DC1=DKA-DC
NC2=INT(1000.*DC1)
C Set up the indices of file names of Green's function, and check whether
C these files exist. If these files exist, then use it directly. Otherwise,
C call subroutine XPQINI1.
FILEEVEN1='E'
FILEODD1='O'
IGE=8*2*(MAXPEG+1)*(MAXPEG+2)
IGO=8*2*(MAXPOG+1)*(MAXPOG+2)
WRITE (FILEEVEN1(2:8),'(I7.7)') NC
WRITE (FILEODD1(2:8),'(I7.7)') NC
WRITE (FILEEVEN1(10:12),'(I3.3)') NC2

```

```

WRITE (FILEODD1(10:12),'(I3.3)') NC2
OPEN (28,ACCESS='DIRECT',FILE=FILEEVEN1,RECL=IGE,IOSTAT=IOS,
+ STATUS='OLD')
  IF (IOS .NE. 0) THEN
    CLOSE (28)
    CALL XPQINI1(DKH,DKA)
  ELSE
    OPEN (29,ACCESS='DIRECT',FILE=FILEODD1,RECL=IGO,IOSTAT=IOS,
+ STATUS='OLD')
    IF (IOS .NE. 0) THEN
      CLOSE (29)
      CALL XPQINI1(DKH,DKA)
    ELSE
      CLOSE (28)
      CLOSE (29)
      CALL XPQINI(DKH,DKA)
    END IF
  ENDIF
RETURN
END

C
  SUBROUTINE XPQINI(DKHIN,DKAIN)
C*****
  INCLUDE 'REALTP.INC'
  INCLUDE 'CMPXTP.INC'
  INCLUDE 'MAINDM.INC'
  DIMENSION GNE(4,(MAXPEG+1)*(MAXPEG+2)/2),
+ GNO(4,(MAXPOG+1)*(MAXPOG+2)/2)
  DIMENSION CGNE(0:MAXPEG,0:MAXPEG,KNDIM1+1),
+ CGNO(0:MAXPOG,0:MAXPOG,KNDIM1+1)
  DIMENSION CDGNE(0:MAXPEG,0:MAXPEG,KNDIM1+1),
+ CDGNO(0:MAXPOG,0:MAXPOG,KNDIM1+1)
  COMMON /CRNTDM/ NMAX,MXNG,IQMAX,IQMAX1,IQMAX2,IXCRNT,ICRNT,MXQEG,
+ MXQOG
  COMMON /GPQTMP/ CGNE,CDGNE,CGNO,CDGNO
  SAVE /GPQTMP/

C
  CHARACTER FILEEVEN1*12, FILEODD1*12
  DKH=DKHIN
  DKA=DKAIN

C
C Initialize the matrix CGNE, CGNO, CDGNE, CDGNO
  DO 105 IC= 1,KNDIM1+1
    DO 102 IB= 0,MAXPEG
      DO 101 IA= 0,MXPEG
        CGNE(IA,IB,IC)=CZERO
        CDGNE(IA,IB,IC)=CZERO
101      CONTINUE
102      CONTINUE
      DO 104 ID=0,MAXPOG
        DO 103 IE=0,MAXPOG
          CGNO(IE,ID,IC)=CZERO
          CDGNO(IE,ID,IC)=CZERO
103        CONTINUE
104      CONTINUE
105    CONTINUE
C
C Set up the file name
  NC1=INT(DKA)
  DC=NC1
  NC=100000.*DKH+NC1
  DC1=DKA-DC
  NC2=INT(1000.*DC1)
  FILEEVEN1='E'
  FILEODD1='O'
  IGE=8*2*(MAXPEG+1)*(MAXPEG+2)
  IGO=8*2*(MAXPOG+1)*(MAXPOG+2)
  WRITE (FILEEVEN1(2:8),'(I7.7)') NC

```

```

WRITE (FILEODD1(2:8),'(I7.7)') NC
WRITE (FILEEVEN1(10:12),'(I3.3)') NC2
WRITE (FILEODD1(10:12),'(I3.3)') NC2
OPEN (28,ACCESS='DIRECT',FILE=FILEEVEN1,RECL=IGE,IOSTAT=IOS,
+      STATUS='OLD')
C
OPEN (29,ACCESS='DIRECT',FILE=FILEODD1,RECL=IGO,IOSTAT=IOS,
+      STATUS='OLD')

DO 900 NI=1,MXNG+1
C   The following values N, DN and DNH are passed to the G-computation
C   related subroutines through the common block /NCONST/.
READ (28,REC=NI) GNE
IRECE=0
DO 500 IQE=0,MXQEG
DO 300 IPE=0,IQE-1
CGNE(IPE,IQE,NI)=CGNE(IQE,IPE,NI)
CDGNE(IPE,IQE,NI)=CDGNE(IQE,IPE,NI)
300 CONTINUE
DO 400 IPE=IQE,MXQEG
IRECE=IRECE+1
GR=GNE(1,IRECE)
GI=GNE(2,IRECE)
GDR=GNE(3,IRECE)
GDI=GNE(4,IRECE)
CGNE(IPE,IQE,NI)=DCMPLX(GR,GI)
CDGNE(IPE,IQE,NI)=DCMPLX(GDR,GDI)
400 CONTINUE
500 CONTINUE
READ (29,REC=NI) GNO
IRECO=0
DO 800 IQO=0,MXQOG
DO 600 IPO=0,IQO-1
CGNO(IPO,IQO,NI)=CGNO(IQO,IPO,NI)
CDGNO(IPO,IQO,NI)=CDGNO(IQO,IPO,NI)
600 CONTINUE
DO 700 IPO=IQO,MXQOG
IRECO=IRECO+1
GR=GNO(1,IRECO)
GI=GNO(2,IRECO)
GDR=GNO(3,IRECO)
GDI=GNO(4,IRECO)
CGNO(IPO,IQO,NI)=DCMPLX(GR,GI)
CDGNO(IPO,IQO,NI)=DCMPLX(GDR,GDI)
700 CONTINUE
800 CONTINUE
900 CONTINUE
CLOSE (28)
CLOSE (29)
RETURN
END

C
SUBROUTINE XPQINI1(DKHIN,DKAIN)
C*****
INCLUDE 'REALTP.INC'
INCLUDE 'CMPXTP.INC'
INCLUDE 'MAINDM.INC'
INCLUDE 'GPQNDM.INC'
INCLUDE 'LIMITS.INC'
DIMENSION GNE(4,(MAXPEG+1)*(MAXPEG+2)/2),
+          GNO(4,(MAXPOG+1)*(MAXPOG+2)/2),
DIMENSION CGNE(0:MAXPEG,0:MAXPEG,KNDIM1+1),
+          CGNO(0:MAXPOG,0:MAXPOG,KNDIM1+1),
DIMENSION CDGNE(0:MAXPEG,0:MAXPEG,KNDIM1+1),
+          CDGNO(0:MAXPOG,0:MAXPOG,KNDIM1+1)
COMMON /CRNTDM/ NMAX,MXNG,IQMAX,IQMAX1,IQMAX2,IXCRNT,ICRNT,MXQEG,
+             MXQOG

```

```

COMMON /GCONST/ DKH,DKA,HH,HA,HSQ,DASQ,HSQN,DASQN,HHSQ,HDASQ,
+ RAH,RAHSQ,DHA,DAH
COMMON /SUMLMT/ DHMAX,DAMAX,DSNG,IHMAX,IAMAX,ISNG
COMMON /NCONST/ DN,DNH,N
COMMON /GPQTMP/ CGNE,CDGNE,CGNO,CDGNO
CHARACTER FILEEVEN1*12, FILEODD1*12
SAVE /GPQTMP/,/GCONST/,/SUMLMT/

C
DKH=DKHIN
DKA=DKAIN
C Initialize the matrix CGNE, CGNO, CDGNE, CDGNO
DO 105 IC= 1,KNDIM1+1
    DO 102 IB= 0,MAXPEG
        DO 101 IA= 0,MXPEG
            CGNE(IA,IB,IC)=CZERO
            CDGNE(IA,IB,IC)=CZERO
101         CONTINUE
102     CONTINUE
        DO 104 ID=0,MAXPOG
            DO 103 IE=0,MAXPOG
                CGNO(IE,ID,IC)=CZERO
                CDGNO(IE,ID,IC)=CZERO
103             CONTINUE
104         CONTINUE
105     CONTINUE
C
C Determine the maximum number of terms for r- and m- series sums and
C pass them through /SUMLMT/:
C
REFC=FZERO*LOG(TWO)-LOG(PI2)-ONE
REFH=HALF*(REFC-LOG(DKH))
REFA=HALF*(REFC-LOG(DKA))
C
IQMX2=IQMAX+2
DHMAX=IQMX2
DO 1100 WHILE ((DHMAX+HALF)*(LOG(DHMAX/DKH)+ONEN) .LT. REFH)
    DHMAX=DHMAX+ONE
1100 CONTINUE
    IHMAX=INT(DHMAX)
C
DAMAX=AINTE(DKA)+ONE
DO 1200 WHILE ((DAMAX+HALF)*(LOG(DAMAX/DKA)+ONEN) .LT. REFA)
    DAMAX=DAMAX+ONE
1200 CONTINUE
C
IAMAX=INT(DAMAX)
C
ISNG=INT(TWO*DKH+ONE-EPS8)
ISNG=MAX(IFPBIT,ISNG,IQMX2)
C Checking dimensions.
IF(IHMAX.GT.MXMREG) THEN
    WRITE(*,*) 'Warning: IHMAX = ',IHMAX,' > MXMREG = ',MXMREG
    WRITE(*,*) 'IHMAX IS SET TO MXMREG IN XPQINI1'
    IHMAX=MXMREG
END IF
ISN1=MXMSNG-N-1
IF(ISNG.GT.ISN1) THEN
    WRITE(*,*) 'Warning: ISNG = ',ISNG,' > MXMSNG-N-1 = ',ISN1
    WRITE(*,*) 'ISNG IS REDUCED TO MXMSNG-N-1 IN XPQINI1'
    ISNG=ISN1
END IF
C
DSNG=ISNG
C
FILEEVEN1='E'
FILEODD1='O'
NC1=INT(DKA)
DC=NC1

```

```

NC=DKH*100000.+NC1
DC1=DKA-DC
NC2=INT(1000.*DC1)
IGE=8*2*(MAXPEG+1)*(MAXPEG+2)
IGO=8*2*(MAXPOG+1)*(MAXPOG+2)
WRITE (FILEEVEN1(2:8),'(I7.7)') NC
WRITE (FILEODD1(2:8),'(I7.7)') NC
WRITE (FILEEVEN1(10:12),'(I3.3)') NC2
WRITE (FILEODD1(10:12),'(I3.3)') NC2
OPEN (28,ACCESS='DIRECT',FILE=FILEEVEN1,RECL=IGE,STATUS='UNKNOWN')
OPEN (29,ACCESS='DIRECT',FILE=FILEODD1,RECL=IGO,STATUS='UNKNOWN')
C Initialize CGNE, CDGNE, CGNO and CDGNO
DO 1900 NI=1,MXNG+1
C The following values N, DN and DNH are passed to the G-computation
C related subroutines through the common block /NCONST/.
N=NI-1
DN=N
DNH=DN+HALF
IRECE=0
DO 1500 IQE=0,MXQEG
IQ=2*IQE
DO 1300 IPE=0,IQE-1
IP=2*IPE
CGNE(IPE,IQE,NI)=CGNE(IQE,IPE,NI)
CDGNE(IPE,IQE,NI)=CDGNE(IQE,IPE,NI)
1300 CONTINUE
DO 1400 IPE=IQE,MXQEG
IRECE=IRECE+1
IP=2*IPE
CALL GDN(IP,IQ,GI,GDI,GR,GDR)
GNE(1,IRECE)=GR
GNE(2,IRECE)=GI
GNE(3,IRECE)=GDR
GNE(4,IRECE)=GDI
CGNE(IPE,IQE,NI)=DCMPLX(GR,GI)
CDGNE(IPE,IQE,NI)=DCMPLX(GDR,GDI)
1400 CONTINUE
1500 CONTINUE
WRITE (28,REC=NI) GNE
IRECO=0
DO 1800 IQO=0,MXQOG
IQ=2*IQO+1
DO 1600 IPO=0,IQO-1
IP=2*IPO+1
CGNO(IPO,IQO,NI)=CGNO(IQO,IPO,NI)
CDGNO(IPO,IQO,NI)=CDGNO(IQO,IPO,NI)
1600 CONTINUE
DO 1700 IPO=IQO,MXQOG
IRECO=IRECO+1
IP=2*IPO+1
CALL GDN(IP,IQ,GI,GDI,GR,GDR)
GNO(1,IRECO)=GR
GNO(2,IRECO)=GI
GNO(3,IRECO)=GDR
GNO(4,IRECO)=GDI
CGNO(IPO,IQO,NI)=DCMPLX(GR,GI)
CDGNO(IPO,IQO,NI)=DCMPLX(GDR,GDI)
1700 CONTINUE
1800 CONTINUE
WRITE (29,REC=NI) GNO
1900 CONTINUE
CLOSE(28)
CLOSE(29)
RETURN
END
C
SUBROUTINE GDN(IPIN,IQIN,GIOUT,GDIOUT,GROUT,GDROUT)
C*****

```

```

C This subrouitne sets up P and Q dependent constants and passes along
C /PCONST/, then calls subroutines GDREG and GDSNG to compute G(P,Q,N)
C and its derivative.
C*****
C
      INCLUDE 'REALTP.INC'
      COMMON /PCONST/ DP,DQ,DS,DD,DSH,DDH,DSSQ,DDSQ,IP,IQ,IS,ID
C Check and transform input variables.
      IP=IPIN
      IQ=IQIN
      ISPQ=IP+IQ
      IS=ISPQ/2
      IF ((ISPQ+1)/2 .GT. IS) THEN
        GIOUT=ZERO
        GDIOUT=ZERO
        GROUT=ZERO
        GDROUT=ZERO
        WRITE (*, 9001) ISPQ
9001  FORMAT('The parameters P and Q have a sum of the ODD integer ',I4,
+/,', G(P, Q, N) and its derivative have been set to 0.')
      RETURN
      END IF
      IF (IP .LT. IQ) THEN
        IP=IQIN
        IQ=IPIN
      END IF
C
      DP=IP
      DQ=IQ
C
      ID=IS-IQ
      DS=IS
      DD=ID
      DSH=DS+HALF
      DDH=DD+HALF
      DSSQ=DS*DS
      DDSQ=DD*DD
C
      CALL GDREG(GI,GDI,GRR,GDRR)
      CALL GDSNG(GRS,GDRS)
      GIOUT=GI
      GDIOUT=GDI
      GROUT=GRR+GRS
      GDROUT=GDRR+GDRS
      RETURN
      END
CC
      SUBROUTINE GDREG(GIOUT,GDIOUT,GROUT,GDROUT)
C*****
C This subrouitne computes the regular part of G(P,Q,N) and its
C derivative.
C*****
C
      INCLUDE 'REALTP.INC'
      INCLUDE 'GPQNDM.INC'
      COMMON /GCONST/ DKH,DKA,HH,HA,HSQ,DASQ,HSQN,DASQN,HHSQ,HDASQ,
+      RAH,RAHSQ,DHA,DAH
      COMMON /NCONST/ DN,DNH,N
      COMMON /PCONST/ DP,DQ,DS,DD,DSH,DDH,DSSQ,DDSQ,IP,IQ,IS,ID
      COMMON /SUMLMT/ DHMAX,DAMAX,DSNG,IHMAX,IAMAX,ISNG
      SAVE /GCONST/,/SUMLMT/
C
C Reserve working space to store r-independent numbers.
      DIMENSION GIM(MXMREG),GRRM(MXMREG)
C
C Computation starts.
C
C Compute overall constant factors:

```



```

      GRRF=QUAR*DKH/PISQ/(DSSQ-QUAR)/(QUAR-DDSQ)/(DN+ONE)
      GIF=HALF/DSH
      DJN=ZERO
      DO 300 JN=1,N
      DJN=DJN+ONE
      HATN=HA/DJN
      GRRF=GRRF*HATN*HATN
      GIF=GIF*HATN*HA/(DJN+DSH)
300    CONTINUE
      DJP=ZERO
      DO 400 JQ=1,IQ
      DJP=DJP+ONE
      GIF=(HHSQ/DJP/DJP)*GIF
400    CONTINUE
      DO 500 JP=IQ+1,IP
      DJP=DJP+ONE
      GIF=(HH/DJP)*GIF
500    CONTINUE
      IF ((ID+1)/2 .GT. ID/2) GIF=-GIF
C
C   Compute GI, GDI, GRREG, and GDRREG.
C   Compute r-independent factors and store in GIM and GRRM:
      SMH=DSH+ONEN
      SM1=DS
      SM2=DS+DS
      PM1=DP
      QM1=DQ
      THRH=HALF
      DM1=ZERO
      THRS=HALF+DS
      THRD=HALF+DD
      THRDN=HALF-DD
      THRSN=HALF-DS
      DO 600 JM=1,IHMAX
      SMH=SMH+ONE
      SM1=SM1+ONE
      SM2=SM2+ONE
      PM1=PM1+ONE
      QM1=QM1+ONE
      THRH=THRH+ONE
      DM1=DM1+ONE
      THRS=THRS+ONE
      THRD=THRD+ONE
      THRDN=THRDN+ONE
      THRSN=THRSN+ONE
      GIM(JM)=(SMH/SM2)*(SMH/PM1)*(SM1/QM1)*(HSQN/DM1)
      GRRM(JM)=(THRH/THRS)*(HSQN/THRD)*(DM1/THRDN)*(DM1/THRSN)
600    CONTINUE
C
C   Compute r- and m-sum for GI and GRR.
C   Setup initial r related values
      DJR=DAMAX
      DNR=DN+DJR
      DNHR=DNR-HALF
      D2NR=DN+DNR
      DNSHR=DNR+DSH
      DN2R=DNR+ONE
C
C   m-sum for r=IAMAX
      DNSHRM=DNSHR+DHMAX
      DN2RM=DN2R+DHMAX
      ANNEXTR=ONE+GIM(IHMAX)/DNSHRM
      ANR0R=ONE+GRRM(IHMAX)/DN2RM
      DO 700 JM=IHMAX-1,1,-1
      DNSHRM=DNSHRM+ONEN
      DN2RM=DN2RM+ONEN
      ANNEXTR=ONE+ANNEXTR*GIM(JM)/DNSHRM
      ANR0R=ONE+ANR0R*GRRM(JM)/DN2RM
700    CONTINUE

```

```

      ANNEXT=ANNEXTR
      DANNEXT=DNR*ANNEXTR
      ANR0=ANR0R
      DANR0=DNR*ANR0R
      DO 900 JR=IAMAX,1,-1
C      Compute factors for r=JR
      ATMP=(DNHR/D2NR)*(DASQN/DJR)
      ATMPI=ATMP/DNSHR
      ATMPR=ATMP/DN2R
C      Setup new r related values for r=JR-1
      DJR=DJR+ONEN
      DNR=DNR+ONEN
      DNHR=DNHR+ONEN
      D2NR=D2NR+ONEN
      DNSHR=DNSHR+ONEN
      DN2R=DN2R+ONEN
C      m-sum for r=JR-1
      DNSHRM=DNSHR+DHMAX
      DN2RM=DN2R+DHMAX
      ANNEXTR=ONE+GIM(IHMAX)/DNSHRM
      ANR0R=ONE+GRRM(IHMAX)/DN2RM
      DO 800 JM=IHMAX-1,1,-1
      DNSHRM=DNSHRM+ONEN
      DN2RM=DN2RM+ONEN
      ANNEXTR=ONE+ANNEXTR*GIM(JM)/DNSHRM
      ANR0R=ONE+ANR0R*GRRM(JM)/DN2RM
800    CONTINUE
      ANNEXT=ANNEXTR+ANNEXT*ATMPI
      DANNEXT=DNR*ANNEXTR+DANNEXT*ATMPI
      ANR0=ANR0R+ANR0*ATMPR
      DANR0=DNR*ANR0R+DANR0*ATMPR
900    CONTINUE
C
      GIOUT=ANNEXT*GIF
      GDIOUT=DANNEXT*GIF
      GROUT=ANR0*GRRF
      GDROUT=DANR0*GRRF
C
      RETURN
      END
C
      SUBROUTINE GDSNG(GROUT,GDROUT)
C*****
C This subrouitne computes the 'singular' part of G(P,Q,N) and its
C derivative.
C*****
C
      INCLUDE 'REALTP.INC'
      INCLUDE 'GPQNDM.INC'
      COMMON /GCONST/ DKH,DKA,HH,HA,HSQ,DASQ,HSQN,DASQN,HHSQ,HDASQ,
+      RAH,RAHSQ,DHA,DAH
      COMMON /NCONST/ DN,DNH,N
      COMMON /PCONST/ DP,DQ,DS,DD,DSH,DDH,DSSQ,DDSQ,IP,IQ,IS,ID
      COMMON /SUMLMT/ DHMAX,DAMAX,DSNG,IHMAX,IAMAX,ISNG
      SAVE /GCONST/,/SUMLMT/
C
C Reserve working space to store r-independent numbers.
      DIMENSION GS1M(MXMSNG),GS2M(MXMSNG),
+      GR2M(MXMSNG),GR2R(0:MXMSNG),GDR2R(0:MXMSNG)
C
C Computation starts.
C
      MXGR2M=ISNG+N
C
C Compute overall constant factors:
      GRSF=QUAR/PISQ/DKH
C
C Compute GR1, GDR1, GR2, and GDR2:

```

```

C      Compute initial constants:

      S1LHA=TWO*LOG (HXD/RAH)
      DK=HALF
      S1SD0=ZERO
      DO 1000 JK=1,ID
      S1SD0=S1SD0+ONE/DK
      DK=DK+ONE
1000    CONTINUE
      S1SD0=TWO*S1SD0
      DO 1100 JK=ID+1, IS
      S1SD0=S1SD0+ONE/DK
      DK=DK+ONE
1100    CONTINUE
      S1SD0=-TWO*S1SD0
      SN0N=ZERO
      SN10=ZERO
      SN20=ZERO
      IF (N .GT. 0) THEN
      DJN=ONE
      DJNH=HALF
      DO 1200 JN=1,N-1
      DJNI=ONE/DJN
      DJNHI=ONE/DJNH
      SN10=DJNI*DJNHI+SN10
      SN20=DJNHI*DJNHI* ((ONE-QUAR*DJNI)*HALF*DJNI+ONE)+SN20
      DJN=DJN+ONE
      DJNH=DJNH+ONE
1200    CONTINUE
      DJNI=ONE/DJN
      DJNHI=ONE/DJNH
      SN0N=S1LHA+HALF*DJNHI-SN10*QUAR
      SN10=(DJNI*DJNHI+SN10)*QUAR
      SN20=HALF*(DJNHI*DJNHI* ((QUAR*DJNI+ONEN)*HALF*DJNI+ONEN)-SN20)
      END IF
      SN10=S1LHA-SN10
      SN20=PISQ*THIR+SN20

C
C      Compute r-independent terms and store in GR2M, GS1M, and GS2M:
      GR2JM=ONE
      S1SDM=S1SD0
      S2SDM=ZERO
      DM=ZERO
      DMH=-HALF
      DO 1300 JM=1,MXGR2M
      DM=DM+ONE
      DMH=DMH+ONE
      DMI=ONE/DM
      DMHI=ONE/DMH
      DMHSQ=DMH*DMH
      DMHSS=DMHSQ-DSSQ
      DMHSD=DMHSQ-DDSQ
      GR2JM=(DMHSS*DMI*DMI)* (DMHSD*DMI*DMHI)*GR2JM
      GR2M(JM)=GR2JM
      TWSMHS=TWO*DSSQ/DMHSS
      TWDMDH=TWO*DDSQ/DMHSD
      S1SDM=S1SDM- (TWSMHS+TWDMDH+DMI+ONE)*DMHI
      S2SDM=S2SDM- ((TWSMHS+THR)*TWSMHS+ (TWDMDH+THR)*TWDMDH+
+      (ONE-QUAR*DMI)*TWO*DMI+ONE)/DMHSQ
      GS1M(JM)=S1SDM
      GS2M(JM)=S2SDM
1300    CONTINUE
C
C      Compute m-sum for GR1, GDR1 and store in GR2R, GDR2R
      IF (N .GT. 0) THEN
      DJR=DN+ONEN
      DJRH=DJR-HALF
      SN0R=SN0N

```

```

SGR1M=SN0R+S1SD0
SDGR1M=DJR*SGR1M+ONEN
DJM=ONE
DJRM=DJR
DO 1400 JM=1,N-1
SR1M=SN0R+GS1M(JM)
HSQF=HSQ/DJM/DJRM
SGR1M=SGR1M*HSQF+SR1M*GR2M(JM)
SDGR1M=SDGR1M*HSQF+(DJR*SR1M+ONEN)*GR2M(JM)
DJM=DJM+ONE
DJRM=DJRM+ONEN
1400 CONTINUE
GR2R(N-1)=SGR1M*TWO
GDR2R(N-1)=SDGR1M*TWO
DO 1600 JR=N-2,0,-1
SN0R=SN0R+ONE/DJRH+ONE/(DN-DJR)-ONE/(DN+DJR)
DJR=DJR+ONEN
DJRH=DJRH+ONEN
SGR1M=SN0R+S1SD0
SDGR1M=DJR*SGR1M+ONEN
DJM=ONE
DJRM=DJR
DO 1500 JM=1,JR
SR1M=SN0R+GS1M(JM)
HSQF=HSQ/DJM/DJRM
SGR1M=SGR1M*HSQF+SR1M*GR2M(JM)
SDGR1M=SDGR1M*HSQF+(DJR*SR1M+ONEN)*GR2M(JM)
DJM=DJM+ONE
DJRM=DJRM+ONEN
1500 CONTINUE
GR2R(JR)=SGR1M*TWO
GDR2R(JR)=SDGR1M*TWO
1600 CONTINUE
END IF
C
C Compute m-sum for GR2, GDR2 and store in GR2R, GDR2R
DRN=DN
SN1R=SN10
SN2R=SN20
SR2MM=SN1R+S1SD0
SR2RMS=SR2MM*SR2MM+SN2R
DR2RMS=DRN*SR2RMS-TWO*SR2MM
DJM=ONE
DJRM=DRN
DO 1700 JM=1,N
SR2MM=SN1R+GS1M(JM)
SR2RM=SR2MM*SR2MM+SN2R+GS2M(JM)
DR2RM=DRN*SR2RM-TWO*SR2MM
HSQF=HSQ/DJM/DJRM
SR2RMS=SR2RMS*HSQF+SR2RM*GR2M(JM)
DR2RMS=DR2RMS*HSQF+DR2RM*GR2M(JM)
DJM=DJM+ONE
DJRM=DJRM+ONEN
1700 CONTINUE
GR2R(N)=SR2RMS
GDR2R(N)=DR2RMS
DJR=ZERO
DO 1900 JR=N+1,MXGR2M
DJR=DJR+ONE
DRN=DRN+ONE
DJRI=ONE/DJR
DRNHI=ONE/(DRN-HALF)
DR2NI=ONE/(DRN+DN)
DNHRF=DNH*DRNHI*DR2NI
SN1R=DJRI-DNHRF+SN1R
SN2R=DJRI*DJRI-(DRNHI+DR2NI)*DNHRF+SN2R
SR2MM=SN1R+S1SD0
SR2RMS=SR2MM*SR2MM+SN2R

```

```

DR2RMS=DRN*SR2RMS-TWO*SR2MM
DJM=ONE
DJRM=DRN
    DO 1800 JM=1,JR
SR2MM=SN1R+GS1M(JM)
SR2RM=SR2MM*SR2MM+SN2R+GS2M(JM)
DR2RM=DRN*SR2RM-TWO*SR2MM
HSQF=HSQ/DJM/DJRM
SR2RMS=SR2RMS*HSQF+SR2RM*GR2M(JM)
DR2RMS=DR2RMS*HSQF+DR2RM*GR2M(JM)
DJM=DJM+ONE
DJRM=DJRM+ONEN
1800    CONTINUE
GR2R(JR)=SR2RMS
GDR2R(JR)=DR2RMS
1900    CONTINUE
C
C    Compute r-sum:
C
C    IF (RAHSQ .GT. HALF) THEN
C
C        Convergence acceleration via Euler-Abel Transformation:
C
DJR=ZERO
DJRH=DJR-HALF
DJRN=DJR+DN
DJRNN=DJR-DN
    IF (N .GT. 0) THEN
RFCTOR=ONE/DN
GR2R(0)=RFCTOR*GR2R(0)
GDR2R(0)=RFCTOR*GDR2R(0)
    DO 2000 JR=1,N-1
DJR=DJR+ONE
DJRH=DJRH+ONE
DJRN=DJRN+ONE
DJRNN=DJRNN+ONE
RFCTOR=(DJR*DJRH/DJRN/DJRNN)*RAHSQ*RFCTOR
GR2R(JR)=RFCTOR*GR2R(JR)
GDR2R(JR)=RFCTOR*GDR2R(JR)
2000    CONTINUE
DJR=DJR+ONE
DJRH=DJRH+ONE
DJRN=DJRN+ONE
DJRNN=DJRNN+ONE
RFCTOR=HALF*(HALF-DN)*RAHSQ*RFCTOR
GR2R(N)=RFCTOR*GR2R(N)
GDR2R(N)=RFCTOR*GDR2R(N)
    ELSE
RFCTOR=ONE
    END IF
    DO 2100 JR=N+1,MXGR2M
DJR=DJR+ONE
DJRH=DJRH+ONE
DJRN=DJRN+ONE
DJRNN=DJRNN+ONE
RFCTOR=(DJR*DJRH/DJRN/DJRNN)*RAHSQ*RFCTOR
GR2R(JR)=RFCTOR*GR2R(JR)
GDR2R(JR)=RFCTOR*GDR2R(JR)
2100    CONTINUE
C
C    Compute zeroth-order delta-r term:
C
    DO 2300 JDELTR=1,MXGR2M
    DO 2200 JR=MXGR2M,JDELTR,-1
GR2R(JR)=GR2R(JR-1)-GR2R(JR)
GDR2R(JR)=GDR2R(JR-1)-GDR2R(JR)
2200    CONTINUE
2300    CONTINUE
SGR2R=HALF*GR2R(MXGR2M)

```

```

SDGR2R=HALF*GDR2R(MXGR2M)
      DO 2400 JR=MXGR2M-1,0,-1
SGR2R=(SGR2R+GR2R(JR))*HALF
SDGR2R=(SDGR2R+GDR2R(JR))*HALF
2400  CONTINUE
      GROUT=GRSF*SGR2R
      GDROUT=GRSF*SDGR2R
C
      ELSE
C
C      Direct summation when RAHSQ is no greater than 1/2:
C
      DJR=DSNG
      DJRN=DJR+DN
      DJRNH=DJRN-HALF
      DJR2N=DJRN+DN
      RFCTOR=(DJRN*DJRNH/DJR/DJR2N)*RAHSQ
      SGR2R=RFCTOR*GR2R(MXGR2M)
      SDGR2R=RFCTOR*GDR2R(MXGR2M)
      DO 2500 JR=MXGR2M-1,N+1,-1
      DJR=DJR+ONEN
      DJRN=DJRN+ONEN
      DJRNH=DJRNH+ONEN
      DJR2N=DJR2N+ONEN
      RFCTOR=(DJRN*DJRNH/DJR/DJR2N)*RAHSQ
      SGR2R=(GR2R(JR)-SGR2R)*RFCTOR
      SDGR2R=(GDR2R(JR)-SDGR2R)*RFCTOR
2500  CONTINUE
      IF (N.EQ. 0) THEN
      GROUT=(GR2R(0)-SGR2R)*GRSF
      GDROUT=(GDR2R(0)-SDGR2R)*GRSF
      ELSE
      RFCTOR=HALF*(HALF-DN)*RAHSQ
      SGR2R=(GR2R(N)-SGR2R)*RFCTOR
      SDGR2R=(GDR2R(N)-SDGR2R)*RFCTOR
      DJR=DN
      DJRH=DJR-HALF
      DJRN=DJR+DN
      DJRNN=DJR-DN
      DO 2600 JR=N-1,1,-1
      DJR=DJR+ONEN
      DJRH=DJRH+ONEN
      DJRN=DJRN+ONEN
      DJRNN=DJRNN+ONEN
      RFCTOR=(DJR*DJRH/DJRN/DJRNN)*RAHSQ
      SGR2R=(GR2R(JR)-SGR2R)*RFCTOR
      SDGR2R=(GDR2R(JR)-SDGR2R)*RFCTOR
2600  CONTINUE
      GROUT=(GR2R(0)-SGR2R)*GRSF/DN
      GDROUT=(GDR2R(0)-SDGR2R)*GRSF/DN
      END IF
      END IF
      RETURN
      END
C

```

## I. SUBROUTINE BCKSCFL

```

      SUBROUTINE BCKSCFL(IR,CESTH,CESPH)
C*****
C
      INCLUDE 'REALTP.INC'
      INCLUDE 'CMPXTP.INC'
      INCLUDE 'MAINDM.INC'
C
      REAL*4 AKPHPR,AKPHPI,AKZPR,AKZPI,ALPHPR,ALPHPI,ALZPR,ALZPI,

```

```

+      AKPHNR, AKPHNI, AKZNR, AKZNI, ALPHNR, ALPHNI, ALZNR, ALZNI
+      DIMENSION CIW(KCRNT), CKLN(KCRNT)
+      DIMENSION CIW0(KXCRT), CKLN0(KXCRT), CXPQN0(KXCRT, KXCRT)
+      DIMENSION CRPQ1(KCRNT, KCRNT), CRPQ2(KCRNT, KCRNT),
+      CXPQN(KCRNT, KCRNT), CXRPQ(KCRNT, KCRNT)
+      DIMENSION CKPHP(61, 61), CKZP(61, 61), CLPHP(61, 61),
+      CLZP(61, 61), CKPHN(61, 61), CKZN(61, 61),
+      CLPHN(61, 61), CLZN(61, 61)
+      COMMON /INPUT2/ IE, IM, THETA, THESINI, THECOSI, RTHEI
+      COMMON /INPUT4/ IZ, IK, IS, NYSM
+      COMMON /NCONST/ DN, DNH, N
+      COMMON /XPQTMP/ CXPQN, CXRPQ, CXPQN0
+      COMMON /XPQTMP1/ CRPQ1, CRPQ2
+      COMMON /CKLMTX/ CKPHP, CKZP, CLPHP, CLZP, CKPHN, CKZN, CLPHN, CLZN
+      COMMON /CRNTDM/ NMAX, MXNG, IQMAX, IQMAX1, IQMAX2, IXCRT, ICRNT, MXQEG,
+      MXQOG
+      COMMON /INPUT3/ RTHE, RDELTA, RPHI, RDELTA, NTHETA, NPHI, THESIN, THECOS,
+      RHPI
+      CESTH=CZERO
+      CESPH=CZERO
+      DO 100 JQ=1, KXCRT
+      CKLN0(JQ)=CZERO
100    CONTINUE
+      DO 200 JQ=1, KCRNT
+      CKLN(JQ)=CZERO
200    CONTINUE
+      DO 400 IF=-30, 30
+      DO 300 JZ=-30, 30
+      CKPHP(IF, JZ)=CZERO
+      CKZP(IF, JZ)=CZERO
+      CLPHP(IF, JZ)=CZERO
+      CLZP(IF, JZ)=CZERO
+      CKPHN(IF, JZ)=CZERO
+      CKZN(IF, JZ)=CZERO
+      CLPHN(IF, JZ)=CZERO
+      CLZN(IF, JZ)=CZERO
300    CONTINUE
400    CONTINUE
C
+      IF (RTHEI .EQ. 0.D0) GO TO 2000
C If incident angle is not equal to 0, use this loop
+      DO 1800 NA=0, NMAX
C
+      CALL INCIDNT(NA, CIW0, CIW)
C
+      IF (NA .EQ. 0) THEN
+      CALL XPQ0
+      ELSE
+      CALL XPQN(NA)
+      ENDIF
C If the cylinder is made of perfect conductor and no coating on it
+      IF (IZ .EQ. 0) THEN
+      DN=NA
C Use IMSL library to solve linear system
+      CALL DLSACG(IXCRT, CXPQN0, KXCRT, CIW0, 1, CKLN0)
+      CALL ESCFAR(NA, CKLN0, CKLN, CETHN, CEPHN)
C
C If we calculate in X and Y components as theta approaches 0 or pi,
C then theta component is cosin phi in X direction plus sine phi in Y
C direction, and phi component is negative sine phi in X direction plus
C cosin phi in Y direction.
+      IF (RTHE .EQ. 0.D0) THEN
+      CETHN=COS(RPHI)*CETHN+SIN(RPHI)*CEPHN
+      CEPHN=-SIN(RPHI)*CETHN+COS(RPHI)*CEPHN
+      ELSEIF (RTHE .EQ. PI) THEN
+      CETHN=-COS(RPHI)*CETHN-SIN(RPHI)*CEPHN
+      CEPHN=-SIN(RPHI)*CETHN+COS(RPHI)*CEPHN
+      END IF

```

```

C
  CESTH=CESTH+CETHN
  CESPH=CESPH+CEPHN
    IF (NA .NE. 0) THEN
      IF (IE .EQ. 1) THEN
        DO 600 I=2,KXCRT,2
          CKLN0(I)=-CKLN0(I)
600    CONTINUE
      END IF
      IF (IM .EQ. 1) THEN
        DO 800 I=1,KXCRT,2
          CKLN0(I)=-CKLN0(I)
800    CONTINUE
      END IF
      NA1=-NA
      DN=NA1
      CALL ESCFAR(NA1,CKLN0,CKLN,CETHN,CEPHN)
        IF (RTHE .EQ. 0.D0) THEN
          CETHN=COS(RPHI)*CETHN+SIN(RPHI)*CEPHN
          CEPHN=-SIN(RPHI)*CETHN+COS(RPHI)*CEPHN
          ELSEIF (RTHE .EQ. PI) THEN
            CETHN=-COS(RPHI)*CETHN-SIN(RPHI)*CEPHN
            CEPHN=-SIN(RPHI)*CETHN+COS(RPHI)*CEPHN
          END IF
C
  CESTH=CESTH+CETHN
  CESPH=CESPH+CEPHN
    END IF
    END IF
C If the cylinder is coated with anisotropic material
  IF (IZ .EQ. 1) THEN
    DO 1100 I=1,KCRNT
      DO 1000 J=1,KCRNT
        CXRPQ(I,J)=CXPQN(I,J)+CRPQ1(I,J)
1000    CONTINUE
1100  CONTINUE
    DN=NA
    CALL DLSACG(ICRNT,CXRPQ,KCRNT,CIW,1,CKLN)
      IF ((IK .EQ. 1) .AND. (IR .EQ. 45)) THEN
        CALL KLCRNT(DN,CKLN,CIW)
      END IF
    CALL ESCFAR(NA,CKLN0,CKLN,CETHN,CEPHN)
      IF (RTHE .EQ. 0.D0) THEN
        CETHN=COS(RPHI)*CETHN+SIN(RPHI)*CEPHN
        CEPHN=-SIN(RPHI)*CETHN+COS(RPHI)*CEPHN
        ELSEIF (RTHE .EQ. PI) THEN
          CETHN=-COS(RPHI)*CETHN-SIN(RPHI)*CEPHN
          CEPHN=-SIN(RPHI)*CETHN+COS(RPHI)*CEPHN
        END IF
C
  CESTH=CESTH+CETHN
  CESPH=CESPH+CEPHN
    IF (NA .NE. 0) THEN
      IF (NYSM .EQ. 0) THEN
        DO 1300 I=1,KCRNT
          DO 1200 J=1,KCRNT
            CXRPQ(I,J)=CXPQN(I,J)+CRPQ2(I,J)
1200    CONTINUE
1300  CONTINUE
      ELSE
        DO 1500 I=1,KCRNT
          DO 1400 J=1,KCRNT
            CXRPQ(I,J)=CXPQN(I,J)+CRPQ1(I,J)
1400    CONTINUE
1500  CONTINUE
      END IF
    CALL DLSACG(ICRNT,CXRPQ,KCRNT,CIW,1,CKLN)
      IF (IE .EQ. 1) THEN

```



```

DO 1600 I=2,KCRNT,4
I1=I+1
CKLN(I)=-CKLN(I)
CKLN(I1)=-CKLN(I1)
1600 CONTINUE
      END IF
      IF (IM .EQ. 1) THEN
DO 1700 I=1,KCRNT,4
I2=I+3
CKLN(I)=-CKLN(I)
CKLN(I2)=-CKLN(I2)
1700 CONTINUE
      END IF
      NA1=-NA
      DN=NA1
      IF ((IK .EQ. 1) .AND. (IS .EQ. 199)) THEN
      CALL KLCRNT(DN,CKLN,CIW)
      END IF
      CALL ESCFAR(NA1,CKLN0,CKLN,CETHN,CEPHN)
      IF (RTHE .EQ. 0.D0) THEN
      CETHN=COS(RPHI)*CETHN+SIN(RPHI)*CEPHN
      CEPHN=-SIN(RPHI)*CETHN+COS(RPHI)*CEPHN
      ELSEIF (RTHE .EQ. PI) THEN
      CETHN=-COS(RPHI)*CETHN-SIN(RPHI)*CEPHN
      CEPHN=-SIN(RPHI)*CETHN+COS(RPHI)*CEPHN
      END IF
C
      CESTH=CESTH+CETHN
      CESPH=CESPH+CEPHN
      END IF
      END IF
1800 CONTINUE
C If the cylinder is coated with anisotropic material and we want to calculate
C equivalent currents K nad L on inner and outer surfaces.
      IF (IK .EQ. 1) THEN
      IF (IS .EQ. 199) THEN
      OPEN(31,FILE='khzz41.dz',STATUS='UNKNOWN')
      OPEN(32,FILE='lhzz41.dz',STATUS='UNKNOWN')
      END IF
      DO 1900 IF=-30,30
      DO 1850 JZ=-30,30
      AKPHPR=REAL(CKPHP(IF,JZ))
      AKPHPI=IMAG(CKPHP(IF,JZ))
      AKZPR=REAL(CKZP(IF,JZ))
      AKZPI=IMAG(CKZP(IF,JZ))
      AKPHNR=REAL(CKPHN(IF,JZ))
      AKPHNI=IMAG(CKPHN(IF,JZ))
      AKZNR=REAL(CKZN(IF,JZ))
      AKZNI=IMAG(CKZN(IF,JZ))
      ALPHPR=REAL(CLPHP(IF,JZ))
      ALPHPI=IMAG(CLPHP(IF,JZ))
      ALZPR=REAL(CLZP(IF,JZ))
      ALZPI=IMAG(CLZP(IF,JZ))
      ALPHNR=REAL(CLPHN(IF,JZ))
      ALPHNI=IMAG(CLPHN(IF,JZ))
      ALZNR=REAL(CLZN(IF,JZ))
      ALZNI=IMAG(CLZN(IF,JZ))
      WRITE(31,*) AKPHPR,' ',AKPHPI
      WRITE(31,*) AKZPR,' ',AKZPI
      WRITE(32,*) ALPHPR,' ',ALPHPI
      WRITE(32,*) ALZPR,' ',ALZPI
      WRITE(31,*) AKPHNR,' ',AKPHNI
      WRITE(31,*) AKZNR,' ',AKZNI
      WRITE(32,*) ALPHNR,' ',ALPHNI
      WRITE(32,*) ALZNR,' ',ALZNI
1850 CONTINUE
1900 CONTINUE
      CLOSE(31)

```

```

CLOSE(32)
END IF
RETURN
C If incident angle is equal to zero, the program should go to this loop
C because it need to compute when n=+1 and n=-1 only.
2000 NA=1
DN=NA
CALL INCIDNT(NA,CIW0,CIW)
CALL XPQN(NA)
C
IF (IZ .EQ. 0) THEN
CALL DLSACG(IXCRNT,CXPQN0,KXCRT,CIW0,1,CKLN0)
CALL ESCFAR(NA,CKLN0,CKLN,CETHN,CEPHN)
C
C If we calculate in X and Y components as theta approaches 0 or pi,
C then theta component is cosin phi in X direction plus sine phi in Y
C direction, and phi component is negative sine phi in X direction plus
C cosin phi in Y direction.
IF (RTHE .EQ. 0.D0) THEN
CETHN=COS(RPHI)*CETHN+SIN(RPHI)*CEPHN
CEPHN=-SIN(RPHI)*CETHN+COS(RPHI)*CEPHN
ELSEIF (RTHE .EQ. PI) THEN
CETHN=-COS(RPHI)*CETHN-SIN(RPHI)*CEPHN
CEPHN=-SIN(RPHI)*CETHN+COS(RPHI)*CEPHN
END IF
C
CESTH=CESTH+CETHN
CESPH=CESPH+CEPHN
IF (NA .NE. 0) THEN
IF (IE .EQ. 1) THEN
DO 2400 I=2,KXCRT,2
CKLN0(I)=-CKLN0(I)
2400 CONTINUE
END IF
IF (IM .EQ. 1) THEN
DO 2500 I=1,KXCRT,2
CKLN0(I)=-CKLN0(I)
2500 CONTINUE
END IF
NA1=-NA
DN=NA1
CALL ESCFAR(NA1,CKLN0,CKLN,CETHN,CEPHN)
IF (RTHE .EQ. 0.D0) THEN
CETHN=COS(RPHI)*CETHN+SIN(RPHI)*CEPHN
CEPHN=-SIN(RPHI)*CETHN+COS(RPHI)*CEPHN
ELSEIF (RTHE .EQ. PI) THEN
CETHN=-COS(RPHI)*CETHN-SIN(RPHI)*CEPHN
CEPHN=-SIN(RPHI)*CETHN+COS(RPHI)*CEPHN
END IF
C
CESTH=CESTH+CETHN
CESPH=CESPH+CEPHN
END IF
END IF
C
IF (IZ .EQ. 1) THEN
DO 3100 I=1,KCRNT
DO 3000 J=1,KCRNT
CXRPQ(I,J)=CXPQN(I,J)+CRPQ1(I,J)
3000 CONTINUE
3100 CONTINUE
DN=NA
CALL DLSACG(ICRNT,CXRPQ,KCRNT,CIW,1,CKLN)
C
IF ((IK .EQ. 1) .AND. (IR .EQ. 45)) THEN
CALL KLCRNT(DN,CKLN,CIW)
END IF
C

```

```

CALL ESCFAR(NA,CKLN0,CKLN,CETHN,CEPHN)
  IF (RTHE .EQ. 0.D0) THEN
    CETHN=COS(RPHI)*CETHN+SIN(RPHI)*CEPHN
    CEPHN=-SIN(RPHI)*CETHN+COS(RPHI)*CEPHN
  ELSEIF (RTHE .EQ. PI) THEN
    CETHN=-COS(RPHI)*CETHN-SIN(RPHI)*CEPHN
    CEPHN=-SIN(RPHI)*CETHN+COS(RPHI)*CEPHN
  END IF

C
  CESTH=CESTH+CETHN
  CESPH=CESPH+CEPHN
  IF (NA .NE. 0) THEN
    IF (NYSM .EQ. 0) THEN
      DO 3300 I=1,KCRNT
        DO 3200 J=1,KCRNT
          CXRPQ(I,J)=CXPQN(I,J)+CRPQ2(I,J)
3200      CONTINUE
3300    CONTINUE
        ELSE
          DO 3500 I=1,KCRNT
            DO 3400 J=1,KCRNT
              CXRPQ(I,J)=CXPQN(I,J)+CRPQ1(I,J)
3400      CONTINUE
3500    CONTINUE
          END IF
        CALL DLSACG(ICRNT,CXRPQ,KCRNT,CIW,1,CKLN)
        IF (IE .EQ. 1) THEN
          DO 3600 I=2,KCRNT,4
            I1=I+1
            CKLN(I)=-CKLN(I)
            CKLN(I1)=-CKLN(I1)
3600      CONTINUE
          END IF
        IF (IM .EQ. 1) THEN
          DO 3700 I=1,KCRNT,4
            I2=I+3
            CKLN(I)=-CKLN(I)
            CKLN(I2)=-CKLN(I2)
3700      CONTINUE
          END IF
        NA1=-NA
        DN=NA1

C
        IF ((IK .EQ. 1) .AND. (IS .EQ. 199)) THEN
          CALL KLCRNT(DN,CKLN,CIW)
          END IF

C
        CALL ESCFAR(NA1,CKLN0,CKLN,CETHN,CEPHN)
        IF (RTHE .EQ. 0.D0) THEN
          CETHN=COS(RPHI)*CETHN+SIN(RPHI)*CEPHN
          CEPHN=-SIN(RPHI)*CETHN+COS(RPHI)*CEPHN
        ELSEIF (RTHE .EQ. PI) THEN
          CETHN=-COS(RPHI)*CETHN-SIN(RPHI)*CEPHN
          CEPHN=-SIN(RPHI)*CETHN+COS(RPHI)*CEPHN
        END IF

C
        CESTH=CESTH+CETHN
        CESPH=CESPH+CEPHN
        END IF
        END IF

C
        IF (IK .EQ. 1) THEN
          IF (IS .EQ. 199) THEN
            OPEN(31,FILE='khzz41.dz',STATUS='UNKNOWN')
            OPEN(32,FILE='lhzz41.dz',STATUS='UNKNOWN')
            END IF
          DO 4200 IF=-30,30
            DO 4100 JZ=-30,30

```

```

      AKPHPR=REAL(CKPHP(IF,JZ))
      AKPHPI=IMAG(CKPHP(IF,JZ))
      AKZPR=REAL(CKZP(IF,JZ))
      AKZPI=IMAG(CKZP(IF,JZ))
      AKPHNR=REAL(CKPHN(IF,JZ))
      AKPHNI=IMAG(CKPHN(IF,JZ))
      AKZNR=REAL(CKZN(IF,JZ))
      AKZNI=IMAG(CKZN(IF,JZ))
      ALPHPR=REAL(CLPHP(IF,JZ))
      ALPHPI=IMAG(CLPHP(IF,JZ))
      ALZPR=REAL(CLZP(IF,JZ))
      ALZPI=IMAG(CLZP(IF,JZ))
      ALPHNR=REAL(CLPHN(IF,JZ))
      ALPHNI=IMAG(CLPHN(IF,JZ))
      ALZNR=REAL(CLZN(IF,JZ))
      ALZNI=IMAG(CLZN(IF,JZ))
      WRITE(31,*) AKPHPR,' ',AKPHPI
      WRITE(31,*) AKZPR,' ',AKZPI
      WRITE(32,*) ALPHPR,' ',ALPHPI
      WRITE(32,*) ALZPR,' ',ALZPI
      WRITE(31,*) AKPHNR,' ',AKPHNI
      WRITE(31,*) AKZNR,' ',AKZNI
      WRITE(32,*) ALPHNR,' ',ALPHNI
      WRITE(32,*) ALZNR,' ',ALZNI
4100      CONTINUE
4200      CONTINUE
      CLOSE(31)
      CLOSE(32)
      END IF
      RETURN
      END

CC
      SUBROUTINE INCIDNT(NA,CIW0,CIW)
C*****
C This subroutine sets up the incident wave on an object which is coated
C with anisotropic material, or a perfect conductor.
C*****
      INCLUDE 'REALTP.INC'
      INCLUDE 'CMPXTP.INC'
      INCLUDE 'MAINDM.INC'

C
      DIMENSION CIW0(KXCRT),CIW(KCRNT),DJNS(KNDIM1+1),DJPS(KQDIM1+2)
      COMMON /INPUT2/ IE,IM,THETAI,THESINI,THECOSI,RTHEI
      COMMON /INPUT4/ IZ,IK,IS,NYSM
      COMMON /INPUT3/ RTHE,RDELT,RPHI,RDELP,NHTTAO,NPHI,THESIN,THECOS,
+      RHPI
      COMMON /RTHETA/ DL1COSI,DL2SINI,DL1
      COMMON /GCONST/ DKH,DKA,HH,HA,HSQ,DASQ,HSQN,DASQN,HHSQ,HDASQ,
+      RAH,RAHSQ,DHA,DAH
      COMMON /CRNTDM/ NMAX,MXNG,IQMAX,IQMAX1,IQMAX2,IXCRNT,ICRNT,MXQEG,
+      MXQOG

C
      NP=NA+1
      NP1=NP+1
      NM=NA-1

C
      IF (IZ .EQ. 0) GO TO 4000

C
C This part computes the incident field on an anisotropic object
C
C Initialize the column matrix of sum current on the anisotropic
      DO 100 IJ=1,KCRNT
      CIW(IJ)=CZERO
100      CONTINUE
C
C If the incident angle is 90 degree or 0 degree
      IF (RTHEI .EQ. ZERO) GO TO 3000
      CALL DBSUNS(DL2SINI, KNDIM1, DJNS)

```

```

      DJN=DJNS(NP)
      IF (NA. EQ. 0) THEN
        DDJN=-DJNS(NP1)
      ELSE
        DDJN=HALF*(DJNS(NA)-DJNS(NP1))
      ENDIF
C Use IMSL library to compute Bessel's function series.
  CALL DBSJNS(DL1COSI,IQMAX2,DJPS)
  DO 600 IP=0,KQDIM
    NIP=IP+1
    DNIP=NIP
    NIP1=NIP+1
    NIP2=NIP+2
    N11=NA+IP-1
    N12=NA+IP
    IE1=MOD(N11,4)
    IE2=MOD(N12,4)

C
    CF1=CI2**IE1
    CF2=CI2**IE2
    IPW1=4*IP+1
    IPW2=IPW1+1
    IPW3=IPW2+1
    IPW4=IPW3+1

C
    DJP=DJPS(NIP)
    DJP1=DJPS(NIP1)
    DJP2=DJPS(NIP2)
    IF (IE .EQ. 1) THEN
      CEEPHI=CF1*(DJP+DJP2)*DDJN/DNIP
      CEHPHI=-TWO*NA*CF2*DJP1*DJN/DLL
      CEHZ=-CF2*THESINI*(DJP+DJP2)*DJN/DNIP
    ELSE
      CEEPHI=CZERO
      CEHPHI=CZERO
      CEHZ=CZERO
    END IF

C
    IF (IM .EQ. 1) THEN
      CMEPHI=TWO*NA*CF2*DJP1*DJN/DLL
      CMEZ=CF2*THESINI*(DJP+DJP2)*DJN/DNIP
      CMHPHI=CF1*(DJP+DJP2)*DDJN/DNIP
    ELSE
      CMEPHI=CZERO
      CMEZ=CZERO
      CMHPHI=CZERO
    END IF

C
    CIW(IPW1)=TWO*(CEEPHI+CMEPHI)
    CIW(IPW2)=TWO*CMEZ
    CIW(IPW3)=TWO*(CEHPHI+CMHPHI)
    CIW(IPW4)=TWO*CEHZ
600  CONTINUE
    RETURN

C
3000 CALL DBSJNS(DKH,IQMAX2,DJPS)
      DO 3200 IP=0,KQDIM
        JP=IP+2
        DJP=DJPS(JP)
        IE11=MOD(IP,4)
        IE12=MOD(IP+1,4)
        CF1=CI2**IE11
        CF2=CI2**IE12
        IPW1=4*IP+1
        IPW3=IPW1+2

C
        IF (IE .EQ. 1) THEN
          CEEPHI=CF1*DJP/DKH

```

```

      CEHPHI=-CF2*DJP/DKH
      ELSE
      CEEPHI=CZERO
      CEHPHI=CZERO
      END IF
C
      IF (IM .EQ. 1) THEN
      CMEPHI=CF2*DJP/DKH
      CMHPHI=CF1*DJP/DKH
      ELSE
      CMEPHI=CZERO
      CMHPHI=CZERO
      END IF
C
      CIW(IPW1)=TWO*(CEEPHI+CMEPHI)
      CIW(IPW3)=TWO*(CEHPHI+CMHPHI)
3200  CONTINUE
      RETURN
C
C   This part compute incident fields on a perfect conductor
C   Initialize the column matrix of sum current on the conductor
4000  DO 4200 IX=1,KXCRT
      CIW0(IX)=CZERO
4200  CONTINUE
C
C   If the incident angle is 90 degree or 0 degree
      IF (RTHEI .EQ. ZERO) GO TO 6000
C
      CALL DBSJNS(DL2SINI, MXNG+1, DJNS)
      DJN=DJNS(NP)
      IF (NA .EQ. 0) THEN
      DDJN=-DJNS(NP1)
      ELSE
      DDJN=HALF*(DJNS(NA)-DJNS(NP1))
      ENDIF
C
      CALL DBSJNS(DL1COSI, IQMAX2, DJPS)
      DO 4400 IP=0,KQDIM
      NIP=IP+1
      DNIP=NIP
      NIP1=NIP+1
      NIP2=NIP+2
      N11=NA+IP-1
      N12=NA+IP
      IE1=MOD(N11,4)
      IE2=MOD(N12,4)
C
      CF1=CI2**IE1
      CF2=CI2**IE2
      IPW1=2*IP+1
      IPW2=IPW1+1
C
      DJP=DJPS(NIP)
      DJP1=DJPS(NIP1)
      DJP2=DJPS(NIP2)
      IF (IE .EQ. 1) THEN
      CEEPHI=CF1*(DJP+DJP2)*DDJN/DNIP
      ELSE
      CEEPHI=CZERO
      END IF
C
      IF (IM .EQ. 1) THEN
      CMEPHI=TWO*NA*CF2*DJP1*DJP/DLL
      CMEZ=CF2*THESINI*(DJP+DJP2)*DJP/DNIP
      ELSE
      CMEPHI=CZERO
      CMEZ=CZERO
      END IF

```

```

C      CIW0(IPW1)=TWO*(CEEPHI+CMEPHI)
C      CIW0(IPW2)=TWO*CMEZ
4400  CONTINUE
      RETURN
C
6000  CALL DBSJNS(DKH,IQMAX2,DJPS)
      DO 6200 IP=0,KQDIM
      JP=IP+2
      DJP=DJPS(JP)
      IE11=MOD(IP,4)
      IE12=MOD(IP+1,4)
      CF1=CI2**IE11
      CF2=CI2**IE12
      IPW1=2*IP+1
C
      IF (IE.EQ. 1) THEN
      CEEPHI=CF1*DJP/DKH
      ELSE
      CEEPHI=CZERO
      END IF
C
      IF (IM.EQ. 1) THEN
      CMEPHI=CF2*DJP/DKH
      ELSE
      CMEPHI=CZERO
      END IF
C
      CIW0(IPW1)=TWO*(CEEPHI+CMEPHI)
6200  CONTINUE
      RETURN
      END
C
      SUBROUTINE XPQ0
C*****
C This subroutine computes the matrix XN(P,Q) for N = 0 following a
C call to XPQINI. This matrix is kept in the common block:
C COMMON /XPQTMP/ CXPQN
C*****
      INCLUDE 'REALTP.INC'
      INCLUDE 'CMPXTP.INC'
      INCLUDE 'MAINDM.INC'
C
      DIMENSION CXPQN(KCRNT,KCRNT),CXRPQ(KCRNT,KCRNT)
      DIMENSION CXPQN0(KXCRT,KXCRT)
      DIMENSION CGNE(0:MAXPEG,0:MAXPEG,KNDIM1+1),
+      CGNO(0:MAXPOG,0:MAXPOG,KNDIM1+1)
      DIMENSION CDGNE(0:MAXPEG,0:MAXPEG,KNDIM1+1),
+      CDGNO(0:MAXPOG,0:MAXPOG,KNDIM1+1)
      COMMON /GPQTMP/ CGNE,CDGNE,CGNO,CDGNO
      COMMON /XPQTMP/ CXPQN,CXRPQ,CXPQN0
      COMMON /CRNTDM/ NMAX,MXNG,IQMAX,IQMAX1,IQMAX2,IXCRNT,ICRNT,MXQEG,
+      MXQOG
      COMMON /GCONST/ DKH,DKA,HH,HA,HSQ,DASQ,HSQN,DASQN,HHSQ,HDASQ,
+      RAH,RAHSQ,DHA,DAH
      COMMON /INPUT4/ IZ,IK,IS,NYSM
      SAVE /XPQTMP/,/GPQTMP/,/GCONST/
C
      IF (N.NE. 0) THEN
      WRITE(*,*) 'Input N is not equal to 0 in XPQ0.'
      WRITE(*,*) 'Execution is stopped.'
      STOP
      END IF
C
      IF (IZ.EQ. 0) GO TO 4000
C
C Initialize the XN(P,Q) matrix.
C Null terms will be skipped later.

```

```

C
DO 200 IQ=1,KCRNT
  DO 100 IP=1,KCRNT
    CXPQN(IP,IQ)=CZERO
100  CONTINUE
200  CONTINUE
C
C Form the XN(P,Q) matrix for n = 0 and using on a perfect conductor
CF31=DKA*CI1
C
DO 1300 IQE=0,MXQEG-1
  IQE1=IQE+1
  IQ=2*IQE
  IQX1=4*IQ+1
  IQX2=IQX1+1
  IQX3=IQX2+1
  IQX4=IQX3+1
  DQ1=IQ+1
  FQ22=DQ1/HHSQ
  DO 1100 IPE=0,MXQEG-1
    IPE1=IPE+1
    IP=2*IPE
    IPX1=4*IP+1
    IPX2=IPX1+1
    IPX3=IPX2+1
    IPX4=IPX3+1
    DP1=IP+1
    F41=DKH/DP1
    CF11=F41*CF31
    F51=QUAR*F41*DKA
    CXPQN(IPX1,IQX1)=(CGNE(IPE1,IQE,2)-CGNE(IPE,IQE,2))*CF11
    CXPQN(IPX4,IQX1)=(CGNE(IPE1,IQE,2)-CGNE(IPE,IQE,2)+HA*(
+      CDGNE(IPE1,IQE,2)-CDGNE(IPE,IQE,2)))*F41
    CXPQN(IPX2,IQX2)=(TWO*FQ22*DP1*CGNO(IPE,IQE,1)+HALF*(
+      CGNE(IPE,IQE1,1)+CGNE(IPE1,IQE,1)-
+      CGNE(IPE1,IQE1,1)-CGNE(IPE,IQE,1)))*CF11
    CXPQN(IPX3,IQX2)=(CDGNE(IPE,IQE,1)+CDGNE(IPE1,IQE1,1)-
+      CDGNE(IPE1,IQE,1)-CDGNE(IPE,IQE1,1))*F51
    CXPQN(IPX2,IQX3)=-CXPQN(IPX4,IQX1)
    CXPQN(IPX3,IQX3)=CXPQN(IPX1,IQX1)
    CXPQN(IPX1,IQX4)=-CXPQN(IPX3,IQX2)
    CXPQN(IPX4,IQX4)=CXPQN(IPX2,IQX2)
1100  CONTINUE
1300  CONTINUE
DO 2300 IQO=0,MXQOG-1
  IQO1=IQO+1
  IQ=2*IQO+1
  IQX1=4*IQ+1
  IQX2=IQX1+1
  IQX3=IQX2+1
  IQX4=IQX3+1
  DQ1=IQ+1
  FQ22=DQ1/HHSQ
  DO 2200 IPO=0,MXQOG-1
    IPO1=IPO+1
    IP=2*IPO+1
    IPX1=4*IP+1
    IPX2=IPX1+1
    IPX3=IPX2+1
    IPX4=IPX3+1
    DP1=IP+1
    F41=DKH/DP1
    CF11=F41*CF31
    F51=QUAR*F41*DKA
    CXPQN(IPX1,IQX1)=(CGNO(IPO1,IQO,2)-CGNO(IPO,IQO,2))*CF11
    CXPQN(IPX4,IQX1)=(CGNO(IPO1,IQO,2)-CGNO(IPO,IQO,2)+HA*(
+      CDGNO(IPO1,IQO,2)-CDGNO(IPO,IQO,2)))*F41
    CXPQN(IPX2,IQX2)=(TWO*FQ22*DP1*CGNE(IPO1,IQO1,1)+HALF*(

```



```

+          CGNO(IPO,IQO1,1)+CGNO(IPO1,IQO,1)-
+          CGNO(IPO1,IQO1,1)-CGNO(IPO,IQO,1)))*CF11
CXPQN(IPX3,IQX2)=(CDGNO(IPO,IQO,1)+CDGNO(IPO1,IQO1,1)-
+          CDGNO(IPO1,IQO,1)-CDGNO(IPO,IQO1,1))*F51
CXPQN(IPX2,IQX3)=-CXPQN(IPX4,IQX1)
CXPQN(IPX3,IQX3)=CXPQN(IPX1,IQX1)
CXPQN(IPX1,IQX4)=-CXPQN(IPX3,IQX2)
CXPQN(IPX4,IQX4)=CXPQN(IPX2,IQX2)
2200    CONTINUE
2300    CONTINUE
      RETURN
C  Initialize the XN(P,Q) matrix.
C  Null terms will be skipped later.
C
4000    DO 4200 IQ=1,KXCRT
          DO 4100 IP=1,KXCRT
            CXPQNO(IP,IQ)=CZERO
4100      CONTINUE
4200    CONTINUE
C
C  Form the XN(P,Q) matrix for n = 0 and using on an anisotropic coat.
      CF31=DKA*CI1
C
      DO 4500 IQE=0,MXQEG-1
        IQE1=IQE+1
        IQ=2*IQE
        IQX1=2*IQ+1
        IQX2=IQX1+1
        DQ1=IQ+1
        FQ22=DQ1/HHSQ
          DO 4400 IPE=0,MXQEG-1
            IPE1=IPE+1
            IPE=2*IPE
            IPX1=2*IP+1
            IPX2=IPX1+1
            DP1=IP+1
            F41=DKH/DP1
            CF11=F41*CF31
            F51=QUAR*F41*DKA
            CXPQNO(IPX1,IQX1)=(CGNE(IPE1,IQE,2)-CGNE(IPE,IQE,2))*CF11
            CXPQNO(IPX2,IQX2)=(TWO*FQ22*DP1*CGNO(IPE,IQE,1)+HALF*(
+              CGNE(IPE,IQE1,1)+CGNE(IPE1,IQE,1)-
+              CGNE(IPE1,IQE1,1)-CGNE(IPE,IQE,1)))*CF11
4400      CONTINUE
4500    CONTINUE
          DO 5300 IQO=0,MXQOG-1
            IQO1=IQO+1
            IQ=2*IQO+1
            IQX1=2*IQ+1
            IQX2=IQX1+1
            DQ1=IQ+1
            FQ22=DQ1/HHSQ
              DO 5200 IPO=0,MXQOG-1
                IPO1=IPO+1
                IP=2*IPO+1
                IPX1=2*IP+1
                IPX2=IPX1+1
                DP1=IP+1
                F41=DKH/DP1
                CF11=F41*CF31
                F51=QUAR*F41*DKA
                CXPQNO(IPX1,IQX1)=(CGNO(IPO1,IQO,2)-CGNO(IPO,IQO,2))*CF11
                CXPQNO(IPX2,IQX2)=(TWO*FQ22*DP1*CGNE(IPO1,IQO1,1)+HALF*(
+                  CGNO(IPO,IQO1,1)+CGNO(IPO1,IQO,1)-
+                  CGNO(IPO1,IQO1,1)-CGNO(IPO,IQO,1)))*CF11
5200      CONTINUE
5300    CONTINUE
          RETURN

```

```

      END
C
      SUBROUTINE XPQN(NIN)
C*****
C This subroutine calls the subroutine GDN to update G(P,Q,N) for
C N = NIN+1, then forms the matrix XN(P,Q) for N = NIN > 0. This matrix
C is kept in the common block:
C   COMMON /XPQTMP/ CXPQN
C*****
C=====
C WARNING:
C IT IS ASSUMED THAT XPQINI AND XPQN FOR N FROM 1 TO NIN-1 HAVE BEEN
C CALLED SO THAT G(P,Q,N) AND ITS DERIVATIVE FOR N=NIN-1 AND N=NIN
C HAVE BEEN STORED IN THE COMMON BLOCK /GPQTMP/ WITH PROPER N-INDICES.
C=====
      INCLUDE 'REALTP.INC'
      INCLUDE 'CMPXTP.INC'
      INCLUDE 'MAINDM.INC'
C
      DIMENSION CXPQN(KCRNT,KCRNT), CXRPQ(KCRNT,KCRNT)
      DIMENSION CXPQN0(KXCRT,KXCRT)
      DIMENSION CGNE(0:MAXPEG,0:MAXPEG,KNDIM1+1),
+             CGNO(0:MAXPOG,0:MAXPOG,KNDIM1+1)
      DIMENSION CDGNE(0:MAXPEG,0:MAXPEG,KNDIM1+1),
+             CDGNO(0:MAXPOG,0:MAXPOG,KNDIM1+1)
      COMMON /GPQTMP/ CGNE,CDGNE,CGNO,CDGNO
      COMMON /XPQTMP/ CXPQN,CXRPQ,CXPQN0
      COMMON /CRNTDM/ NMAX,MXNG,IQMAX,IQMAX1,IQMAX2,IXCRNT,ICRNT,MXQEG,
+             MXQOG
      COMMON /GCONST/ DKH,DKA,HH,HA,HSQ,DASQ,HSQN,DASQN,HHSQ,HDASQ,
+             RAH,RAHSQ,DHA,DAH
      COMMON /NCONST/ DN,DNH,N
      COMMON /INPUT4/ IZ,IK,IS,NYSM
      SAVE /XPQTMP//,GPQTMP//,GCONST/
C
      N=NIN
      NA=ABS(N)
      IF (NA .LT. 1) THEN
        WRITE(*,*) 'Input ABS(N) is less than 1 in XPQN.'
        WRITE(*,*) 'Execution is stopped.'
        STOP
      END IF
C
      NOI=NA+1
      NPI=NOI+1
      NMI=NA
C
      DN0=NA
      DNP=NOI
      DNM=NA-1
C
      IF (IZ .EQ. 0) GO TO 4000
C
C Initialize the XN(P,Q) matrix.
C Null terms will be skipped later.
C
      DO 800 IQ=1,KCRNT
        DO 700 IP=1,KCRNT
          CXPQN(IP,IQ)=CZERO
700      CONTINUE
800      CONTINUE
C
C Form the XN(P,Q) matrix.
      CF31=DKA*CI1
      F21=TWO*DN0
      FN11=F21*DN0/DASQ
C
      DO 1300 IQE=0,MXQEG-1

```

```

IQE1=IQE+1
IQ=2*IQE
IQX1=4*IQ+1
IQX2=IQX1+1
IQX3=IQX2+1
IQX4=IQX3+1
DQ1=IQ+1
FQ12=DN0*DQ1
FQ22=DQ1/HHSQ
    DO 1100 IPE=0,MXQEG-1
IPE1=IPE+1
IP=2*IPE
IPX1=4*IP+1
IPX2=IPX1+1
IPX3=IPX2+1
IPX4=IPX3+1
DP1=IP+1
F41=HH/DP1
CF11=F41*CF31
F51=HALF*DKA*F41
CXPQN(IPX1,IQX1)=( (CGNE(IPE,IQE,N0I)-CGNE(IPE1,IQE,N0I))*FN11+
+ CGNE(IPE1,IQE,NMI)-CGNE(IPE,IQE,NMI)+
+ CGNE(IPE1,IQE,NPI)-CGNE(IPE,IQE,NPI))*CF11
CXPQN(IPX4,IQX1)=( (CGNE(IPE,IQE,NMI)-CGNE(IPE1,IQE,NMI))*DNM+
+ (CGNE(IPE1,IQE,NPI)-CGNE(IPE,IQE,NPI))*DNP+
+ HA*(CDGNE(IPE1,IQE,NMI)-CDGNE(IPE,IQE,NMI)+
+ CDGNE(IPE1,IQE,NPI)-CDGNE(IPE,IQE,NPI))*F41
CXPQN(IPX2,IQX2)=(FQ22*DP1*CGNO(IPE,IQE,N0I)+
+ CGNE(IPE,IQE1,N0I)+CGNE(IPE1,IQE,N0I)-
+ CGNE(IPE1,IQE1,N0I)-CGNE(IPE,IQE,N0I))*CF11
CXPQN(IPX3,IQX2)=(CDGNE(IPE,IQE,N0I)+CDGNE(IPE1,IQE1,N0I)-
+ CDGNE(IPE1,IQE,N0I)-CDGNE(IPE,IQE1,N0I))*F51
CXPQN(IPX2,IQX3)=-CXPQN(IPX4,IQX1)
CXPQN(IPX3,IQX3)=CXPQN(IPX1,IQX1)
CXPQN(IPX1,IQX4)=-CXPQN(IPX3,IQX2)
CXPQN(IPX4,IQX4)=CXPQN(IPX2,IQX2)
1100    CONTINUE
        DO 1200 IPO=0,MXQOG-1
IPO1=IPO+1
IP=2*IPO+1
IPX1=4*IP+1
IPX2=IPX1+1
IPX3=IPX2+1
IPX4=IPX3+1
DP1=IP+1
F12=FQ12/DP1
CXPQN(IPX2,IQX1)=F21*CGNE(IPO1,IQE,N0I)
CXPQN(IPX3,IQX1)=(CGNE(IPO1,IQE,NMI)-CGNE(IPO1,IQE,NPI))*CF31
CXPQN(IPX1,IQX2)=(CGNO(IPO1,IQE,N0I)-CGNO(IPO,IQE,N0I))*F12
CXPQN(IPX1,IQX3)=-CXPQN(IPX3,IQX1)
CXPQN(IPX4,IQX3)=CXPQN(IPX2,IQX1)
CXPQN(IPX3,IQX4)=CXPQN(IPX1,IQX2)
1200    CONTINUE
1300    CONTINUE
        DO 2300 IQO=0,MXQOG-1
IQO1=IQO+1
IQ=2*IQO+1
IQX1=4*IQ+1
IQX2=IQX1+1
IQX3=IQX2+1
IQX4=IQX3+1
DQ1=IQ+1
FQ12=DN0*DQ1
FQ22=DQ1/HHSQ
    DO 2100 IPE=0,MXQEG-1
IPE1=IPE+1
IP=2*IPE
IPX1=4*IP+1

```

```

IPX2=IPX1+1
IPX3=IPX2+1
IPX4=IPX3+1
DP1=IP+1
F12=FQ12/DP1
CXPQN(IPX2,IQX1)=F21*CGNO(IPE,IQO,N0I)
CXPQN(IPX3,IQX1)=(CGNO(IPE,IQO,NMI)-CGNO(IPE,IQO,NPI))*CF31
CXPQN(IPX1,IQX2)=(CGNE(IPE1,IQO1,N0I)-CGNE(IPE,IQO1,N0I))*F12
CXPQN(IPX1,IQX3)=-CXPQN(IPX3,IQX1)
CXPQN(IPX4,IQX3)=CXPQN(IPX2,IQX1)
CXPQN(IPX3,IQX4)=CXPQN(IPX1,IQX2)
2100    CONTINUE
        DO 2200 IPO=0,MXQOG-1
IPO1=IPO+1
IP=2*IPO+1
IPX1=4*IP+1
IPX2=IPX1+1
IPX3=IPX2+1
IPX4=IPX3+1
DP1=IP+1
F41=HH/DP1
CF11=F41*CF31
F51=HALF*DKA*F41
CXPQN(IPX1,IQX1)=( (CGNO(IPO,IQO,N0I)-CGNO(IPO1,IQO,N0I))*FN11+
+      CGNO(IPO1,IQO,NMI)-CGNO(IPO,IQO,NMI)+
+      CGNO(IPO1,IQO,NPI)-CGNO(IPO,IQO,NPI))*CF11
CXPQN(IPX4,IQX1)=( (CGNO(IPO,IQO,NMI)-CGNO(IPO1,IQO,NMI))*DNM+
+      (CGNO(IPO1,IQO,NPI)-CGNO(IPO,IQO,NPI))*DNP+
+      HA*(CDGNO(IPO1,IQO,NMI)-CDGNO(IPO,IQO,NMI)+
+      CDGNO(IPO1,IQO,NPI)-CDGNO(IPO,IQO,NPI)))*F41
CXPQN(IPX2,IQX2)=(FQ22*DP1*CGNE(IPO1,IQO1,N0I)+
+      CGNO(IPO,IQO1,N0I)+CGNO(IPO1,IQO,N0I)-
+      CGNO(IPO1,IQO1,N0I)-CGNO(IPO,IQO,N0I))*CF11
CXPQN(IPX3,IQX2)=(CDGNO(IPO,IQO,N0I)+CDGNO(IPO1,IQO1,N0I)-
+      CDGNO(IPO1,IQO,N0I)-CDGNO(IPO,IQO1,N0I))*F51
CXPQN(IPX2,IQX3)=-CXPQN(IPX4,IQX1)
CXPQN(IPX3,IQX3)=CXPQN(IPX1,IQX1)
CXPQN(IPX1,IQX4)=-CXPQN(IPX3,IQX2)
CXPQN(IPX4,IQX4)=CXPQN(IPX2,IQX2)
2200    CONTINUE
2300    CONTINUE
        RETURN
C   Initialize the XN(P,Q) matrix.
C   Null terms will be skipped later.
C
4000    DO 4800 IQ=1,KXCRT
        DO 4700 IP=1,KXCRT
CXPQN0(IP,IQ)=CZERO
4700    CONTINUE
4800    CONTINUE
C
C   Form the XN(P,Q) matrix.
CF31=DKA*CI1
F21=TWO*DN0
FN11=F21*DN0/DASQ
C
        DO 5300 IQE=0,MXQEG-1
IQE1=IQE+1
IQ=2*IQE
IQX1=2*IQ+1
IQX2=IQX1+1
DQ1=IQ+1
FQ12=DN0*DQ1
FQ22=DQ1/HHSQ
        DO 5100 IPE=0,MXQEG-1
IPE1=IPE+1
IP=2*IPE
IPX1=2*IP+1

```

```

IPX2=IPX1+1
DP1=IP+1
F41=HH/DP1
CF11=F41*CF31
F51=HALF*DKA*F41
CXPQN0(IPX1,IQX1)=(CGNE(IPE,IQE,N0I)-CGNE(IPE1,IQE,N0I))*FN11+
+ CGNE(IPE1,IQE,NMI)-CGNE(IPE,IQE,NMI)+
+ CGNE(IPE1,IQE,NPI)-CGNE(IPE,IQE,NPI))*CF11
CXPQN0(IPX2,IQX2)=(FQ22*DP1*CGNO(IPE,IQE,N0I)+
+ CGNE(IPE,IQE1,N0I)+CGNE(IPE1,IQE,N0I)-
+ CGNE(IPE1,IQE1,N0I)-CGNE(IPE,IQE,N0I))*CF11
5100 CONTINUE
DO 5200 IPO=0,MXQOG-1
IPO1=IPO+1
IP=2*IPO+1
IPX1=2*IP+1
IPX2=IPX1+1
DP1=IP+1
F12=FQ12/DP1
CXPQN0(IPX2,IQX1)=F21*CGNE(IPO1,IQE,N0I)
CXPQN0(IPX1,IQX2)=(CGNO(IPO1,IQE,N0I)-CGNO(IPO,IQE,N0I))*F12
5200 CONTINUE
5300 CONTINUE
DO 6300 IQO=0,MXQOG-1
IQO1=IQO+1
IQ=2*IQO+1
IQX1=2*IQ+1
IQX2=IQX1+1
DQ1=IQ+1
FQ12=DN0*DQ1
FQ22=DQ1/HHSQ
DO 6100 IPE=0,MXQEG-1
IPE1=IPE+1
IP=2*IPE
IPX1=2*IP+1
IPX2=IPX1+1
DP1=IP+1
F12=FQ12/DP1
CXPQN0(IPX2,IQX1)=F21*CGNO(IPE,IQO,N0I)
CXPQN0(IPX1,IQX2)=(CGNE(IPE1,IQO1,N0I)-CGNE(IPE,IQO1,N0I))*F12
6100 CONTINUE
DO 6200 IPO=0,MXQOG-1
IPO1=IPO+1
IP=2*IPO+1
IPX1=2*IP+1
IPX2=IPX1+1
DP1=IP+1
F41=HH/DP1
CF11=F41*CF31
F51=HALF*DKA*F41
CXPQN0(IPX1,IQX1)=(CGNO(IPO,IQO,N0I)-CGNO(IPO1,IQO,N0I))*FN11+
+ CGNO(IPO1,IQO,NMI)-CGNO(IPO,IQO,NMI)+
+ CGNO(IPO1,IQO,NPI)-CGNO(IPO,IQO,NPI))*CF11
CXPQN0(IPX2,IQX2)=(FQ22*DP1*CGNE(IPO1,IQO1,N0I)+
+ CGNO(IPO,IQO1,N0I)+CGNO(IPO1,IQO,N0I)-
+ CGNO(IPO1,IQO1,N0I)-CGNO(IPO,IQO,N0I))*CF11
6200 CONTINUE
6300 CONTINUE
RETURN
END

C
SUBROUTINE ESCFAR(NIN,CKLN0,CKLN,CETHN,CEPHN)
C*****
C This subroutine computes the scattered fields in far zone
C
INCLUDE 'REALTP.INC'
INCLUDE 'CMPXTP.INC'
INCLUDE 'MAINDM.INC'

```

```

C      DIMENSION CKLN0(KXCRT)
      DIMENSION CKLN(KCRNT),DJNS(KNDIM1),DJPS(KQDIM1+2)
      COMMON /CRNTDM/ NMAX,MXNG,IQMAX,IQMAX1,IQMAX2,IXCRNT,ICRNT,MXQEG,
+      MXQOG
      COMMON /GCONST/ DKH,DKA,HH,HA,HSQ,DASQ,HSQN,DASQN,HHSQ,HDASQ,
+      RAH,RAHSQ,DHA,DAH
      COMMON /INPUT3/ RTHE,RDELT,RPHI,RDELP,NHTAO,NPHI,THESIN,THECOS,
+      RHPI
      COMMON /INPUT4/ IZ,IK,IS,NYSM

C      N=NIN
      DN1=N
      NA=ABS(NIN)
      NP=NA+1
      NP1=NP+1
      PHI1=RPHI*N
      CI2N=CI2**N
      CENP=CONE*COS(PHI1)+CI1*SIN(PHI1)
      CETHN=CZERO
      CEPHN=CZERO

C      IF ((RTHE .EQ. 0.) .OR. (RTHE .EQ. PI)) GO TO 2000

C      TCOT=THECOS/THESIN
      DL2SIN=DKA*THESIN
      DL1COS=DKH*THECOS
      DNL2=DN1*TCOT/DKA
      CALL DBSJNS(DL2SIN, KNDIM1, DJNS)

C      DJN=DJNS(NP)
      IF (N .EQ. 0) THEN
      DDJN=-DJNS(NP1)
      ELSE
      DDJN=HALF*(DJNS(NA)-DJNS(NP1))
      ENDIF

C      KN=NA/2
      KNP=NP/2
      IF ((N .LT. 0) .AND. (KNP .GT. KN)) THEN
      DJN=-DJN
      DDJN=-DDJN
      ENDIF

C      CALL DBSJNS(DL1COS, KQDIM1+2, DJPS)

C      IF (IZ .EQ. 0) THEN
      DO 100 IP=0,IQMAX
      INP=IP+1
      NP2=INP+2
      N11=IP
      N12=IP+2
      IE1=MOD(N11,4)
      CF1=CI2**IE1
      IPW1=2*IP+1
      IPW2=IPW1+1
      DJP=DJPS(INP)
      DJP2=DJPS(NP2)
      DJPH=HALF*(DJP+DJP2)
      CETHN=CETHN+CI2N*DHA*CENP*CI1*CF1*DJN*(DNL2*CKLN0(IPW1)*DJP
+      -THESIN*CKLN0(IPW2)*DJPH)
      CEPHN=CEPHN-CI2N*DHA*CENP*DDJN*CKLN0(IPW1)*CF1*DJP
100  CONTINUE
      ELSE
      DO 200 IP=0,IQMAX
      INP=IP+1
      NP2=INP+2
      N11=IP

```

```

N12=IP+2
IE1=MOD(N11,4)
CF1=CI2**IE1
IPW1=4*IP+1
IPW2=IPW1+1
IPW3=IPW2+1
IPW4=IPW3+1
DJP=DJPS(INP)
DJP2=DJPS(NP2)
DJPH=HALF*(DJP+DJP2)
CETHN=CETHN+CI2N*DHA*CENP*((CI1*DJN*DNL2*CKLN(IPW1)-DDJN
+ *CKLN(IPW3))*DJP-CI1*DJN*THESIN*CKLN(IPW2)*DJPH)*CF1
CEPHN=CEPHN-CI2N*DHA*CENP*((DDJN*CKLN(IPW1)+CI1*DJN*DNL2
+ *CKLN(IPW3))*DJP-CI1*DJN*THESIN*CKLN(IPW4)*DJPH)*CF1
200 CONTINUE
    END IF
    RETURN
C
2000 IF (NA .NE. 1) THEN
    GO TO 3000
    END IF
    CALL DBSJNS(DKH,KQDIM1,DJPS)
C
    IF (IZ .EQ. 0) THEN
    DO 2100 IP=0,IQMAX
    INP=IP+1
    IPW1=2*IP+1
    JP=MOD(IP,4)
    CF1=CI1**JP
    CF2=CI2**JP
C
    DJP=DJPS(INP)
    IF (RTHE .EQ. 0.) THEN
    IF (N .LT. 0) THEN
    CETHN=CETHN-DAH*DJP*CF2*CKLN0(IPW1)
    CEPHN=CEPHN+DAH*DJP*CF2*CI1*CKLN0(IPW1)
    ELSE
    CETHN=CETHN+DAH*DJP*CF2*CKLN0(IPW1)
    CEPHN=CEPHN+DAH*DJP*CF2*CI1*CKLN0(IPW1)
    END IF
    END IF
    IF (RTHE .EQ. PI) THEN
    IF (N .LT. 0) THEN
    CETHN=CETHN-DAH*DJP*CF1*CKLN0(IPW1)
    CEPHN=CEPHN+DAH*DJP*CF1*CI1*CKLN0(IPW1)
    ELSE
    CETHN=CETHN+DAH*DJP*CF1*CKLN0(IPW1)
    CEPHN=CEPHN+DAH*DJP*CF1*CI1*CKLN0(IPW1)
    END IF
    END IF
2100 CONTINUE
    ELSE
    DO 2200 IP=0,IQMAX
    INP=IP+1
    IPW1=4*IP+1
    IPW3=IPW1+2
    JP=MOD(IP,4)
    CF1=CI1**JP
    CF2=CI2**JP
C
    DJP=DJPS(INP)
    IF (RTHE .EQ. 0.) THEN
    IF (N .LT. 0) THEN
    CETHN=CETHN-DAH*DJP*CF2*(CKLN(IPW1)-CI1*CKLN(IPW3))
    CEPHN=CEPHN+DAH*DJP*CF2*(CI1*CKLN(IPW1)+CKLN(IPW3))
    ELSE
    CETHN=CETHN+DAH*DJP*CF2*(CKLN(IPW1)+CI1*CKLN(IPW3))
    CEPHN=CEPHN+DAH*DJP*CF2*(CI1*CKLN(IPW1)-CKLN(IPW3))

```

```

        END IF
        END IF
        IF (RTHE .EQ. PI) THEN
            IF (N .LT. 0) THEN
                CETHN=CETHN-DAH*DJP*CF1*(CKLN(IPW1)+CI1*CKLN(IPW3))
                CEPHN=CEPHN+DAH*DJP*CF1*(CI1*CKLN(IPW1)-CKLN(IPW3))
            ELSE
                CETHN=CETHN+DAH*DJP*CF1*(CKLN(IPW1)-CI1*CKLN(IPW3))
                CEPHN=CEPHN+DAH*DJP*CF1*(CI1*CKLN(IPW1)+CKLN(IPW3))
            END IF
        END IF
2200    CONTINUE
        END IF
3000    RETURN
        END
C
        SUBROUTINE KLCRNT(DN,CKLN,CIW)
C*****
C This subroutine computes equivalent currents K and L on inner and outer
C surfaces respectively.
        INCLUDE 'REALTP.INC'
        INCLUDE 'CMPXTP.INC'
        INCLUDE 'MAINDM.INC'
C
        DIMENSION CKLN(KCRNT),CIW(KCRNT)
        DIMENSION CKLNP(KCRNT),CKLNN(KCRNT)
        DIMENSION CRPQ31(KCRNT,KCRNT),CRPQ32(KCRNT,KCRNT)
        DIMENSION CKPHP(61,61),CKZP(61,61),CLPHP(61,61),
+          CLZP(61,61),CKPHN(61,61),CKZN(61,61),
+          CLPHN(61,61),CLZN(61,61)
        COMMON /CKLMTX/ CKPHP,CKZP,CLPHP,CLZP,CKPHN,CKZN,CLPHN,CLZN
        COMMON /XPQTMP2/ CRPQ31,CRPQ32
        COMMON /CRNTDM/ NMAX,MXNG,IQMAX,IQMAX1,IQMAX2,IXCRNT,ICRNT,MXQEG,
+          MXQOG
        COMMON /INPUT3/ RTHE,RDELT,RPHI,RDELP,NHTTAO,NPHI,THESIN,THECOS,
+          RHPI
        COMMON /INPUT4/ IZ,IK,IS,NYSM
C
        DO 400 IX=1,ICRNT
            CKLNP(IX)=CZERO
            CKLNN(IX)=CZERO
400    CONTINUE
            PHI1=DN*RPHI
            CPHI=CONE*COS(PHI1)+CI1*SIN(PHI1)
C
            DO 600 IX=1,ICRNT
                DO 500 IY=1,ICRNT
                    CKLNP(IX)=CKLNP(IX)+CRPQ31(IX,IY)*CKLN(IY)
500    CONTINUE
600    CONTINUE
C
            DO 800 IX=1,ICRNT
                DO 700 IY=1,ICRNT
                    CKLNN(IX)=CKLNN(IX)+CRPQ32(IX,IY)*CKLN(IY)
700    CONTINUE
800    CONTINUE
C
            DO 1600 IF=-30,30
                DF=IF
                DPHI=DF*PI/32.D0
                DNPHI=DN*DPHI
                CPHI=CONE*DCOS(DNPHI)+CI1*DSIN(DNPHI)
                DO 1500 JZ=-30,30
                    DJZ=JZ
                    DZ=DJZ/32.D0
                    DV=DACOS(DZ)
                    SINVD=DSIN(DV)

```



```

C
CKPHP(IF,JZ)=CZERO
CKZP(IF,JZ)=CZERO
CLPHP(IF,JZ)=CZERO
CLZP(IF,JZ)=CZERO
CKPHN(IF,JZ)=CZERO
CKZN(IF,JZ)=CZERO
CLPHN(IF,JZ)=CZERO
CLZN(IF,JZ)=CZERO

C
      DO 1400 IP=0,IQMAX
      P=IP
      P1=IP+1
      DPV=P*DV
      DP1V=P1*DV
      DCSPV=DCOS(DPV)
      SINP1V=DSIN(DP1V)
      IPX1=IP*4+1
      IPX2=IPX1+1
      IPX3=IPX2+1
      IPX4=IPX3+1
      CKPHP(IF,JZ)=CKPHP(IF,JZ)+CPHI*(CKLNP(IPX1)+CIW(IPX4))
+      *DCSPV/PI/SINV
      CKZP(IF,JZ)=CKZP(IF,JZ)+CPHI*(CKLNP(IPX2)-CIW(IPX3))*SINP1V/PI
      CLPHP(IF,JZ)=CLPHP(IF,JZ)+CPHI*(CKLNP(IPX3)-CIW(IPX2))
+      *DCSPV/PI/SINV
      CLZP(IF,JZ)=CLZP(IF,JZ)+CPHI*(CKLNP(IPX4)+CIW(IPX1))*SINP1V/PI
      CKPHN(IF,JZ)=CKPHN(IF,JZ)+CPHI*(CKLNN(IPX1)-CIW(IPX4))
+      *DCSPV/PI/SINV
      CKZN(IF,JZ)=CKZN(IF,JZ)+CPHI*(CKLNN(IPX2)+CIW(IPX3))*SINP1V/PI
      CLPHN(IF,JZ)=CLPHN(IF,JZ)+CPHI*(CKLNN(IPX3)+CIW(IPX2))
+      *DCSPV/PI/SINV
      CLZN(IF,JZ)=CLZN(IF,JZ)+CPHI*(CKLNN(IPX4)-CIW(IPX1))*SINP1V/PI
1400      CONTINUE
1500      CONTINUE
1600      CONTINUE
      RETURN
      END

```

## J. SUBROUTINE RCSPAREA

```

      SUBROUTINE RCSPAREA(CESTH,CESPH)
C*****
C This subroutine computes cross section per projected area in all direction.
C
      INCLUDE 'REALTP.INC'
      INCLUDE 'CMPXTP.INC'
C
      REAL*4 ARCSPPA1,ARCSPPA2,APHASE1,APHASE2
      COMMON /GCONST/ DKH,DKA,HH,HA,HSQ,DASQ,HSQN,DASQN,HHSQ,HDASQ,
+      RAH,RAHSQ,DHA,DAH
      COMMON /INPUT3/ RTHE,RDELT,RPHI,RDELP,NTHTAO,NPHI,THESIN,THECOS,
+      RHPI
C
      ESTH=ABS(CESTH)
      ESPH=ABS(CESPH)
      ESTHSQ=ESTH*ESTH
      ESPHSQ=ESPH*ESPH
      IF (RTHE.EQ. RHPI) THEN
      RCSPPA1=PI*ESTHSQ/DKH/DKA
      RCSPPA2=PI*ESPHSQ/DKH/DKA
      ELSE IF ((RTHE.EQ. ZERO) .OR. (RTHE.EQ. PI)) THEN
      RCSPPA1=4.D0*ESTHSQ/DASQ
      RCSPPA2=4.D0*ESPHSQ/DASQ
      ELSE

```

```

AP=ABS (QUAR*DASQ*THECOS) +ABS (DKH*DKA*THESIN/PI)
RCSPPA1=ESTHSQ/AP
RCSPPA2=ESPHSQ/AP
      END IF
ARCSPPA1=RCSPPA1
ARCSPPA2=RCSPPA2
C
ER1=REAL (CESTH)
EI1=IMAG (CESTH)
ER2=REAL (CESPH)
EI2=IMAG (CESPH)
PHASE1=DATAN2 (EI1,ER1)
PHASE2=DATAN2 (EI2,ER2)
APHASE1=PHASE1
APHASE2=PHASE2
WRITE (21,*) ARCSPPA1,APHASE1,ARCSPPA2,APHASE2
C
RETURN
END

```

## LIST OF REFERENCES

- [1] M. E. Morris, private communication.
- [2] J. A. Stratton and L. J. Chu, "Diffraction Theory of Electromagnetic Waves." *Physical Rev.*, Vol. 56, pp.99-107, 1939.
- [3] C. Müller, *Foundations of the Mathematical Theory of Electromagnetic Waves*, Springer-Verlag, 1969.
- [4] V. H. Weston, "Theory of Absorbers in Scattering," *IEEE Trans. Antennas Propagat.*, Vol 11, 1963.
- [5] R. E. Collin, *Field Theory of Guided Waves*, Sec. 1.5, IEEE Press, 1991.
- [6] H.-M. Lee, "Electromagnetic Scattering of Tubular Cylindrical Structure--Double Series Formulation and Some Results," *IEEE Trans. Antennas Propagat.*, Vol. AP-35, No.4, pp. 384-390 1987.
- [7] H.-M. Lee, C. P. Chung, D. Geller and B. Haklay, " $H_{11}$  Circular Waveguide Mode and Back Scattering Cross Section Along the Axis of a Thin Walled Tubular Cylinder of Finite Length," *IEE Proceedings*, Vol. 133, Pt. H., pp. 77-78, 1986



## INITIAL DISTRIBUTION LIST

|    |                                                                                                                                    | No. Copies |
|----|------------------------------------------------------------------------------------------------------------------------------------|------------|
| 1. | Defense Technical Information Center<br>8725 John J. Kingman Rd., STE 0944<br>Ft. Belvoir, VA 22060-6218                           | 2          |
| 2. | Dudley Knox Library,<br>Naval Postgraduate School<br>411 Dyer Rd.<br>Monterey, CA 93943-5101                                       | 2          |
| 3. | Chairman, Code EC<br>Department of Electrical and Computer Engineering<br>Naval Postgraduate School<br>Monterey, CA 93943-5121     | 1          |
| 4. | Hung-Mou Lee, EC/Lh<br>Department of Electrical and Computer Engineering<br>Naval Postgraduate School<br>Monterey, CA 93943-5121   | 2          |
| 5. | David C. Jenn, EC/Jn<br>Department of Electrical and Computer Engineering<br>Naval Postgraduate School<br>Monterey, CA 93943-5121  | 1          |
| 6. | Sherif Michael, EC/Mi<br>Department of Electrical and Computer Engineering<br>Naval Postgraduate School<br>Monterey, CA 93943-5121 | 1          |
| 7. | Peter C. Chu, OC/Cu<br>Department of Oceanography<br>Naval Postgraduate School<br>Monterey, CA 93943-5121                          | 1          |
| 8. | Fariba Fahroo, MA/Ff<br>Department of Mathematics<br>Naval Postgraduate School                                                     | 1          |

Monterey, CA 93943-5121

- |     |                                                                                                                       |   |
|-----|-----------------------------------------------------------------------------------------------------------------------|---|
| 9.  | Dr. Marvine E. Morris<br>Sandia National Laboratories<br>Organization 2753<br>P. O. Box 5800<br>Albuquerque, NM 87158 | 1 |
| 10. | Chen-Kuo Yu<br>4F-2, 282, Tong-Men Rd<br>Ku-Shan Distr., Kaohsung<br>Taiwan, ROC                                      | 2 |
| 11. | Library<br>Naval Academy<br>Tsoyn, Kaohsung<br>Taiwan, ROC                                                            | 1 |